Software Testing & Component-Based Software Engineering

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Table of Contents

Chapter 1

Software Testing

Software testing is an investigation conducted to provide stakeholders with information about the quality of the product or service under test. Software testing also provides an objective, independent view of the software to allow the business to appreciate and understand the risks of software implementation. Test techniques include, but are not limited to, the process of executing a program or application with the intent of finding software bugs.

Software testing can also be stated as the process of validating and verifying that a software program/application/product:

1. meets the business and technical requirements that guided its design and development;
2. works as expected; and
3. can be implemented with the same characteristics.

Software testing, depending on the testing method employed, can be implemented at any time in the development process. However, most of the test effort occurs after the requirements have been defined and the coding process has been completed. As such, the methodology of the test is governed by the software development methodology adopted.

Different software development models will focus the test effort at different points in the development process. Newer development models, such as Agile, often employ test driven development and place an increased portion of the testing in the hands of the developer, before it reaches a formal team of testers. In a more traditional model, most of the test execution occurs after the requirements have been defined and the coding process has been completed.

Overview

Testing can never completely identify all the defects within software. Instead, it furnishes a *criticism* or *comparison* that compares the state and behavior of the product against oracles—principles or mechanisms by which someone might recognize a problem. These oracles may include (but are not limited to) specifications, contracts, comparable products, past versions of the same product, inferences about intended or expected purpose, user or customer expectations, relevant standards, applicable laws, or other criteria.

Every software product has a target audience. For example, the audience for video game software is completely different from banking software. Therefore, when an organization develops or otherwise invests in a software product, it can assess whether the software product will be acceptable to its end users, its target audience, its purchasers, and other stakeholders. **Software testing** is the process of attempting to make this assessment.

A study conducted by NIST in 2002 reports that software bugs cost the U.S. economy $59.5 billion annually. More than a third of this cost could be avoided if better software testing was performed.

History

The separation of debugging from testing was initially introduced by Glenford J. Myers in 1979. Although his attention was on breakage testing ("a successful test is one that finds a bug") it illustrated the desire of the software engineering community to separate fundamental development activities, such as debugging, from that of verification. Dave Gelperin and William C. Hetzel classified in 1988 the phases and goals in software testing in the following stages:

- Until 1956 - Debugging oriented
- 1957–1978 - Demonstration oriented
- 1979–1982 - Destruction oriented
- 1983–1987 - Evaluation oriented
- 1988–2000 - Prevention oriented

Software testing topics

Scope

A primary purpose of testing is to detect software failures so that defects may be discovered and corrected. This is a non-trivial pursuit. Testing cannot establish that a product functions properly under all conditions but can only establish that it does not function properly under specific conditions. The scope of software testing often includes examination of code as well as execution of that code in various environments and conditions as well as examining the aspects of code: does it do what it is supposed to do and do what it needs to do. In the current culture of software development, a testing organization may be separate from the development team. There are various roles for testing team members. Information derived from software testing may be used to correct the process by which software is developed.

Functional vs non-functional testing

Functional testing refers to activities that verify a specific action or function of the code. These are usually found in the code requirements documentation, although some development methodologies work from use cases or user stories. Functional tests tend to answer the question of "can the user do this" or "does this particular feature work".

Non-functional testing refers to aspects of the software that may not be related to a specific function or user action, such as scalability or security. Non-functional testing tends to answer such questions as "how many people can log in at once".

Defects and failures

Not all software defects are caused by coding errors. One common source of expensive defects is caused by requirement gaps, e.g., unrecognized requirements, that result in errors of omission by the program designer. A common source of requirements gaps is non-functional requirements such as testability, scalability, maintainability, usability, performance, and security.

Software faults occur through the following processes. A programmer makes an error (mistake), which results in a defect (fault, bug) in the software source code. If this defect is executed, in certain situations the system will produce wrong results, causing a failure. Not all defects will necessarily result in failures. For example, defects in dead code will never result in failures. A defect can turn into a failure when the environment is changed. Examples of these changes in environment include the software being run on a new hardware platform, alterations in source data or interacting with different software. A single defect may result in a wide range of failure symptoms.

Finding faults early

It is commonly believed that the earlier a defect is found the cheaper it is to fix it. The following table shows the cost of fixing the defect depending on the stage it was found. For example, if a problem in the requirements is found only post-release, then it would cost 10–100 times more to fix than if it had already been found by the requirements review.

Cost to fix a defect		**Time detected**				
		Requirements	**Architecture**	**Construction**	**System test**	**Post-release**
Time introduced	**Requirements**	1×	3×	5–10×	10×	10–100×
	Architecture	-	1×	10×	15×	25–100×
	Construction	-	-	1×	10×	10–25×

Compatibility

A common cause of software failure (real or perceived) is a lack of compatibility with other application software, operating systems (or operating system versions, old or new), or target environments that differ greatly from the original (such as a terminal or GUI application intended to be run on the desktop now being required to become a web application, which must render in a web browser). For example, in the case of a lack of backward compatibility, this can occur because the programmers develop and test software only on the latest version of the target environment, which not all users may be running. This results in the unintended consequence that the latest work may not function on earlier versions of the target environment, or on older hardware that earlier versions of the target environment was capable of using. Sometimes such issues can be fixed by proactively abstracting operating system functionality into a separate program module or library.

Input combinations and preconditions

A very fundamental problem with software testing is that testing under *all* combinations of inputs and preconditions (initial state) is not feasible, even with a simple product. This means that the number of defects in a software product can be very large and defects that occur infrequently are difficult to find in testing. More significantly, non-functional dimensions of quality (how it is supposed to *be* versus what it is supposed to *do*)—usability, scalability, performance, compatibility, reliability—can be highly subjective; something that constitutes sufficient value to one person may be intolerable to another.

Static vs. dynamic testing

There are many approaches to software testing. Reviews, walkthroughs, or inspections are considered as static testing, whereas actually executing programmed code with a given set of test cases is referred to as dynamic testing. Static testing can be (and unfortunately in practice often is) omitted. Dynamic testing takes place when the program itself is used for the first time (which is generally considered the beginning of the testing stage). Dynamic testing may begin before the program is 100% complete in order to test particular sections of code (modules or discrete functions). Typical techniques for this are either using stubs/drivers or execution from a debugger environment. For example, spreadsheet programs are, by their very nature, tested to a large extent interactively ("on the fly"), with results displayed immediately after each calculation or text manipulation.

Software verification and validation

Software testing is used in association with verification and validation:

- Verification: Have we built the software right? (i.e., does it match the specification).
- Validation: Have we built the right software? (i.e., is this what the customer wants).

The terms verification and validation are commonly used interchangeably in the industry; it is also common to see these two terms incorrectly defined. According to the IEEE Standard Glossary of Software Engineering Terminology:

> Verification is the process of evaluating a system or component to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase.
> Validation is the process of evaluating a system or component during or at the end of the development process to determine whether it satisfies specified requirements.

The software testing team

Software testing can be done by software testers. Until the 1980s the term "software tester" was used generally, but later it was also seen as a separate profession. Regarding the periods and the different goals in software testing, different roles have been established: *manager*, *test lead*, *test designer*, *tester*, *automation developer*, and *test administrator*.

Software quality assurance (SQA)

Though controversial, software testing may be viewed as an important part of the software quality assurance (SQA) process. In SQA, software process specialists and auditors take a broader view on software and its development. They examine and change the software engineering process itself to reduce the amount of faults that end up in the delivered software: the so-called *defect rate.*

What constitutes an "acceptable defect rate" depends on the nature of the software; A flight simulator video game would have much higher defect tolerance than software for an actual airplane.

Although there are close links with SQA, testing departments often exist independently, and there may be no SQA function in some companies.

Software testing is a task intended to detect defects in software by contrasting a computer program's expected results with its actual results for a given set of inputs. By contrast, QA (quality assurance) is the implementation of policies and procedures intended to prevent defects from occurring in the first place.

Testing methods

The box approach

Software testing methods are traditionally divided into white- and black-box testing. These two approaches are used to describe the point of view that a test engineer takes when designing test cases.

White box testing

White box testing is when the tester has access to the internal data structures and algorithms including the code that implement these.

Types of white box testing

The following types of white box testing exist:

- API testing (application programming interface) - testing of the application using public and private APIs
- Code coverage - creating tests to satisfy some criteria of code coverage (e.g., the test designer can create tests to cause all statements in the program to be executed at least once)
- Fault injection methods - improving the coverage of a test by introducing faults to test code paths
- Mutation testing methods
- Static testing - White box testing includes all static testing

Test coverage

White box testing methods can also be used to evaluate the completeness of a test suite that was created with black box testing methods. This allows the software team to examine parts of a system that are rarely tested and ensures that the most important function points have been tested.

Two common forms of code coverage are:

- *Function coverage*, which reports on functions executed
- *Statement coverage*, which reports on the number of lines executed to complete the test

They both return a code coverage metric, measured as a percentage.

Black box testing

Black box testing treats the software as a "black box"—without any knowledge of internal implementation. Black box testing methods include: equivalence partitioning, boundary value analysis, all-pairs testing, fuzz testing, model-based testing, traceability matrix, exploratory testing and specification-based testing.

Specification-based testing: Specification-based testing aims to test the functionality of software according to the applicable requirements. Thus, the tester inputs data into, and only sees the output from, the test object. This level of testing usually requires thorough test cases to be provided to the tester, who then can simply verify that for a given input, the output value (or behavior), either "is" or "is not" the same as the expected value specified in the test case.
Specification-based testing is necessary, but it is insufficient to guard against certain risks.

Advantages and disadvantages: The black box tester has no "bonds" with the code, and a tester's perception is very simple: a code *must* have bugs. Using the principle, "Ask and you shall receive," black box testers find bugs where programmers do not. On the other hand, black box testing has been said to be "like a walk in a dark labyrinth without a flashlight," because the tester doesn't know how the software being tested was actually constructed. As a result, there are situations when (1) a tester writes many test cases to check something that could have been tested by only one test case, and/or (2) some parts of the back-end are not tested at all.

Therefore, black box testing has the advantage of "an unaffiliated opinion", on the one hand, and the disadvantage of "blind exploring", on the other.

Grey box testing

Grey box testing (American spelling: **gray box testing**) involves having knowledge of internal data structures and algorithms for purposes of designing the test cases, but testing at the user, or black-box level. Manipulating input data and formatting output do not qualify as grey box, because the input and output are clearly outside of the "black-box" that we are calling the system under test. This distinction is particularly important when conducting integration testing between two modules of code written by two different developers, where only the interfaces are exposed for test. However, modifying a data repository does qualify as grey box, as the user would not normally be able to change the data outside of the system under test. Grey box testing may also include reverse engineering to determine, for instance, boundary values or error messages.

Testing levels

Tests are frequently grouped by where they are added in the software development process, or by the level of specificity of the test.

Unit testing

Unit testing refers to tests that verify the functionality of a specific section of code, usually at the function level. In an object-oriented environment, this is usually at the class level, and the minimal unit tests include the constructors and destructors.

These type of tests are usually written by developers as they work on code (white-box style), to ensure that the specific function is working as expected. One function might have multiple tests, to catch corner cases or other branches in the code. Unit testing alone cannot verify the functionality of a piece of software, but rather is used to assure that the building blocks the software uses work independently of each other.

Unit testing is also called *component testing*.

Integration testing

Integration testing is any type of software testing that seeks to verify the interfaces between components against a software design. Software components may be integrated in an iterative way or all together ("big bang"). Normally the former is considered a better practice since it allows interface issues to be localised more quickly and fixed.

Integration testing works to expose defects in the interfaces and interaction between integrated components (modules). Progressively larger groups of tested software components corresponding to elements of the architectural design are integrated and tested until the software works as a system.

System testing

System testing tests a completely integrated system to verify that it meets its requirements.

System integration testing

System integration testing verifies that a system is integrated to any external or third-party systems defined in the system requirements.

Regression testing

Regression testing focuses on finding defects after a major code change has occurred. Specifically, it seeks to uncover software regressions, or old bugs that have come back. Such regressions occur whenever software functionality that was previously working correctly stops working as intended. Typically, regressions occur as an unintended consequence of program changes, when the newly developed part of the software collides with the previously existing code. Common methods of regression testing include re-running previously run tests and checking whether previously fixed faults have re-emerged. The depth of testing depends on the phase in the release process and the risk of the added features. They can either be complete, for changes added late in the release or deemed to be risky, to very shallow, consisting of positive tests on each feature, if the changes are early in the release or deemed to be of low risk.

Acceptance testing

Acceptance testing can mean one of two things:

1. A smoke test is used as an acceptance test prior to introducing a new build to the main testing process, i.e. before integration or regression.
2. Acceptance testing performed by the customer, often in their lab environment on their own hardware, is known as user acceptance testing (UAT). Acceptance testing may be performed as part of the hand-off process between any two phases of development.

Alpha testing

Alpha testing is simulated or actual operational testing by potential users/customers or an independent test team at the developers' site. Alpha testing is often employed for off-the-shelf software as a form of internal acceptance testing, before the software goes to beta testing.

Beta testing

Beta testing comes after alpha testing and can be considered a form of external user acceptance testing. Versions of the software, known as beta versions, are released to a limited audience outside of the programming team. The software is released to groups of people so that further testing can ensure the product has few faults or bugs. Sometimes, beta versions are made available to the open public to increase the feedback field to a maximal number of future users.

Non-functional testing

Special methods exist to test non-functional aspects of software. In contrast to functional testing, which establishes the correct operation of the software (correct in that it matches the expected behavior defined in the design requirements), non-functional testing verifies that the software functions properly even when it receives invalid or unexpected inputs. Software fault injection, in the form of fuzzing, is an example of non-functional testing. Non-functional testing, especially for software, is designed to establish whether the device under test can tolerate invalid or unexpected inputs, thereby establishing the robustness of input validation routines as well as error-handling routines. Various commercial non-functional testing tools are linked from the software fault injection page; there are also numerous open-source and free software tools available that perform non-functional testing.

Software performance testing and load testing

Performance testing is executed to determine how fast a system or sub-system performs under a particular workload. It can also serve to validate and verify other quality attributes of the system, such as scalability, reliability and resource usage. Load testing is primarily concerned with testing that can continue to operate under a specific load, whether that be large quantities of data or a large number of users. This is generally referred to as software scalability. The related load testing activity of when performed as a non-functional activity is often referred to as *endurance testing*.

Volume testing is a way to test functionality. *Stress testing* is a way to test reliability. *Load testing* is a way to test performance. There is little agreement on what the specific goals of load testing are. The terms load testing, performance testing, reliability testing, and volume testing, are often used interchangeably.

Stability testing

Stability testing checks to see if the software can continuously function well in or above an acceptable period. This activity of non-functional software testing is often referred to as load (or endurance) testing.

Usability testing

Usability testing is needed to check if the user interface is easy to use and understand.

Security testing

Security testing is essential for software that processes confidential data to prevent system intrusion by hackers.

Internationalization and localization

The general ability of software to be internationalized and localized can be automatically tested without actual translation, by using pseudolocalization. It will verify that the application still works, even after it has been translated into a new language or adapted for a new culture (such as different currencies or time zones).

Actual translation to human languages must be tested, too. Possible localization failures include:

- Software is often localized by translating a list of strings out of context, and the translator may choose the wrong translation for an ambiguous source string.
- If several people translate strings, technical terminology may become inconsistent.
- Literal word-for-word translations may sound inappropriate, artificial or too technical in the target language.
- Untranslated messages in the original language may be left hard coded in the source code.
- Some messages may be created automatically in run time and the resulting string may be ungrammatical, functionally incorrect, misleading or confusing.
- Software may use a keyboard shortcut which has no function on the source language's keyboard layout, but is used for typing characters in the layout of the target language.
- Software may lack support for the character encoding of the target language.
- Fonts and font sizes which are appropriate in the source language, may be inappropriate in the target language; for example, CJK characters may become unreadable if the font is too small.
- A string in the target language may be longer than the software can handle. This may make the string partly invisible to the user or cause the software to fail.
- Software may lack proper support for reading or writing bi-directional text.
- Software may display images with text that wasn't localized.

- Localized operating systems may have differently-named system configuration files and environment variables and different formats for date and currency.

To avoid these and other localization problems, a tester who knows the target language must run the program with all the possible use cases for translation to see if the messages are readable, translated correctly in context and don't cause failures.

Destructive testing

Destructive testing attempts to cause the software or a sub-system to fail, in order to test its robustness.

The testing process

Traditional CMMI or waterfall development model

A common practice of software testing is that testing is performed by an independent group of testers after the functionality is developed, before it is shipped to the customer. This practice often results in the testing phase being used as a project buffer to compensate for project delays, thereby compromising the time devoted to testing.

Another practice is to start software testing at the same moment the project starts and it is a continuous process until the project finishes.

Agile or Extreme development model

In counterpoint, some emerging software disciplines such as extreme programming and the agile software development movement, adhere to a "test-driven software development" model. In this process, unit tests are written first, by the software engineers (often with pair programming in the extreme programming methodology). Of course these tests fail initially; as they are expected to. Then as code is written it passes incrementally larger portions of the test suites. The test suites are continuously updated as new failure conditions and corner cases are discovered, and they are integrated with any regression tests that are developed. Unit tests are maintained along with the rest of the software source code and generally integrated into the build process (with inherently interactive tests being relegated to a partially manual build acceptance process). The ultimate goal of this test process is to achieve continuous deployment where software updates can be published to the public frequently.

A sample testing cycle

Although variations exist between organizations, there is a typical cycle for testing. The sample below is common among organizations employing the Waterfall development model.

- **Requirements analysis**: Testing should begin in the requirements phase of the software development life cycle. During the design phase, testers work with developers in determining what aspects of a design are testable and with what parameters those tests work.
- **Test planning**: Test strategy, test plan, testbed creation. Since many activities will be carried out during testing, a plan is needed.
- **Test development**: Test procedures, test scenarios, test cases, test datasets, test scripts to use in testing software.
- **Test execution**: Testers execute the software based on the plans and test documents then report any errors found to the development team.
- **Test reporting**: Once testing is completed, testers generate metrics and make final reports on their test effort and whether or not the software tested is ready for release.
- **Test result analysis**: Or Defect Analysis, is done by the development team usually along with the client, in order to decide what defects should be treated, fixed, rejected (i.e. found software working properly) or deferred to be dealt with later.
- **Defect Retesting**: Once a defect has been dealt with by the development team, it is retested by the testing team. AKA Resolution testing.
- **Regression testing**: It is common to have a small test program built of a subset of tests, for each integration of new, modified, or fixed software, in order to ensure that the latest delivery has not ruined anything, and that the software product as a whole is still working correctly.
- **Test Closure**: Once the test meets the exit criteria, the activities such as capturing the key outputs, lessons learned, results, logs, documents related to the project are archived and used as a reference for future projects.

Automated testing

Many programming groups are relying more and more on automated testing, especially groups that use test-driven development. There are many frameworks to write tests in, and continuous integration software will run tests automatically every time code is checked into a version control system.

While automation cannot reproduce everything that a human can do (and all the ways they think of doing it), it can be very useful for regression testing. However, it does require a well-developed test suite of testing scripts in order to be truly useful.

Testing tools

Program testing and fault detection can be aided significantly by testing tools and debuggers. Testing/debug tools include features such as:

- Program monitors, permitting full or partial monitoring of program code including:

    - Instruction set simulator, permitting complete instruction level monitoring and trace facilities
    - Program animation, permitting step-by-step execution and conditional breakpoint at source level or in machine code
    - Code coverage reports
- Formatted dump or symbolic debugging, tools allowing inspection of program variables on error or at chosen points
- Automated functional GUI testing tools are used to repeat system-level tests through the GUI
- Benchmarks, allowing run-time performance comparisons to be made
- Performance analysis (or profiling tools) that can help to highlight hot spots and resource usage

Some of these features may be incorporated into an Integrated Development Environment (IDE).

Measurement in software testing

Usually, quality is constrained to such topics as correctness, completeness, security, but can also include more technical requirements as described under the ISO standard ISO/IEC 9126, such as capability, reliability, efficiency, portability, maintainability, compatibility, and usability.

There are a number of frequently-used software measures, often called *metrics*, which are used to assist in determining the state of the software or the adequacy of the testing.

Testing artifacts

Software testing process can produce several artifacts.

Test plan

A test specification is called a test plan. The developers are well aware what test plans will be executed and this information is made available to management and the developers. The idea is to make them more cautious when developing their code or making additional changes. Some companies have a higher-level document called a test strategy.

Traceability matrix

A traceability matrix is a table that correlates requirements or design documents to test documents. It is used to change tests when the source documents are changed, or to verify that the test results are correct.

Test case

A test case normally consists of a unique identifier, requirement references from a design specification, preconditions, events, a series of steps (also known as actions) to follow, input, output, expected result, and actual result. Clinically defined a test case is an input and an expected result. This can be as pragmatic as 'for condition x your derived result is y', whereas other test cases described in more detail the input scenario and what results might be expected. It can occasionally be a series of steps (but often steps are contained in a separate test procedure that can be exercised against multiple test cases, as a matter of economy) but with one expected result or expected outcome. The optional fields are a test case ID, test step, or order of execution number, related requirement(s), depth, test category, author, and check boxes for whether the test is automatable and has been automated. Larger test cases may also contain prerequisite states or steps, and descriptions. A test case should also contain a place for the actual result. These steps can be stored in a word processor document, spreadsheet, database, or other common repository. In a database system, you may also be able to see past test results, who generated the results, and what system configuration was used to generate those results. These past results would usually be stored in a separate table.

Test script

The test script is the combination of a test case, test procedure, and test data. Initially the term was derived from the product of work created by automated regression test tools. Today, test scripts can be manual, automated, or a combination of both.

Test suite

The most common term for a collection of test cases is a test suite. The test suite often also contains more detailed instructions or goals for each collection of test cases. It definitely contains a section where the tester identifies the system configuration used during testing. A group of test cases may also contain prerequisite states or steps, and descriptions of the following tests.

Test data

In most cases, multiple sets of values or data are used to test the same functionality of a particular feature. All the test values and changeable environmental components are collected in separate files and stored as test data. It is also useful to provide this data to the client and with the product or a project.

Test harness

The software, tools, samples of data input and output, and configurations are all referred to collectively as a test harness.

Certifications

Several certification programs exist to support the professional aspirations of software testers and quality assurance specialists. No certification currently offered actually requires the applicant to demonstrate the ability to test software. No certification is based on a widely accepted body of knowledge. This has led some to declare that the testing field is not ready for certification. Certification itself cannot measure an individual's productivity, their skill, or practical knowledge, and cannot guarantee their competence, or professionalism as a tester.

Software testing certification types

- *Exam-based*: Formalized exams, which need to be passed; can also be learned by self-study [e.g., for ISTQB or QAI]
- *Education-based*: Instructor-led sessions, where each course has to be passed [e.g., International Institute for Software Testing (IIST)].

Testing certifications

- Certified Associate in Software Testing (CAST) offered by the Quality Assurance Institute (QAI)
- CATe offered by the *International Institute for Software Testing*
- Certified Manager in Software Testing (CMST) offered by the Quality Assurance Institute (QAI)
- Certified Software Tester (CSTE) offered by the Quality Assurance Institute (QAI)
- Certified Software Test Professional (CSTP) offered by the *International Institute for Software Testing*
- CSTP (TM) (Australian Version) offered by *K. J. Ross & Associates*
- ISEB offered by the Information Systems Examinations Board
- ISTQB Certified Tester, Foundation Level (CTFL) offered by the International Software Testing Qualification Board
- ISTQB Certified Tester, Advanced Level (CTAL) offered by the International Software Testing Qualification Board
- TMPF TMap Next Foundation offered by the *Examination Institute for Information Science*
- TMPA TMap Next Advanced offered by the *Examination Institute for Information Science*

Quality assurance certifications

- CMSQ offered by the *Quality Assurance Institute* (QAI).
- CSQA offered by the *Quality Assurance Institute* (QAI)
- CSQE offered by the American Society for Quality (ASQ)
- CQIA offered by the American Society for Quality (ASQ)

Controversy

Some of the major software testing controversies include:

What constitutes responsible software testing?

Members of the "context-driven" school of testing believe that there are no "best practices" of testing, but rather that testing is a set of skills that allow the tester to select or invent testing practices to suit each unique situation.

Agile vs. traditional

Should testers learn to work under conditions of uncertainty and constant change or should they aim at process "maturity"? The agile testing movement has received growing popularity since 2006 mainly in commercial circles, whereas government and military software providers are slow to embrace this methodology in favour of traditional test-last models (e.g. in the Waterfall model).

Exploratory test vs. scripted

Should tests be designed at the same time as they are executed or should they be designed beforehand?

Manual testing vs. automated

Some writers believe that test automation is so expensive relative to its value that it should be used sparingly. More in particular, test-driven development states that developers should write unit-tests of the XUnit type before coding the functionality. The tests then can be considered as a way to capture and implement the requirements.

Software design vs. software implementation

Should testing be carried out only at the end or throughout the whole process?

Who watches the watchmen?

The idea is that any form of observation is also an interaction—the act of testing can also affect that which is being tested.

Chapter 2

Application Programming Interface and Code Coverage

Application programming interface

An **Application Programming Interface** (**API**) is a particular set of rules and specifications that a software program can follow to access and make use of the services and resources provided by another particular software program that implements that API. It serves as an interface between different software programs and facilitates their interaction, similar to the way the user interface facilitates interaction between humans and computers.

An API can be created for applications, libraries, operating systems, etc, as a way to define their "vocabularies" and resources request conventions (e.g. functions calling conventions). It may include specifications for routines, data structures, object classes, and protocols used to communicate between the consumer program and the implementer program of the API.

Concept

An API is an abstraction that describes an interface for the interaction with a set of functions used by components of a software system. The software providing the functions described by an API is said to be an *implementation* of the API.

An API can be:

- general, the full set of an API that is bundled in the libraries of a programming language, e.g. Standard Template Library in C++ or Java API.
- specific, meant to address a specific problem, e.g. Google Maps API or Java API for XML Web Services.
- language-dependent, meaning it is only available by using the syntax and elements of a particular language, which makes the API more convenient to use.

- language-independent, written so that it can be called from several programming languages. This is a desirable feature for a service-oriented API that is not bound to a specific process or system and may be provided as remote procedure calls or web services. For example, a website that allows users to review local restaurants is able to layer their reviews over maps taken from Google Maps, because Google Maps has an API that facilitates this functionality. Google Maps' API controls what information a third-party site can use and how they can use it.

API may be used to refer to a complete interface, a single function, or even a set of APIs provided by an organization. Thus, the scope of meaning is usually determined by the context of usage.

Advanced explanation

An API may describe the ways in which a particular task is performed. For example, in Unix systems, the `math.h` include file for the C language contains the definition of the mathematical functions available in the C language library for mathematical processing (usually called `libm`). This file would describe how to use these functions and the expected result. For example, on a Unix system the command `man 3 sqrt` will present the signature of the function `sqrt` in the form:

```
SYNOPSIS
            #include <math.h>
            double sqrt(double X);
            float  sqrtf(float X);
DESCRIPTION
       DESCRIPTION
       sqrt computes the positive square root of the argument. ...
RETURNS
       On success, the square root is returned. If X is real and
positive...
```

that means that the function returns the square root of a positive floating point number (`single` or `double` precision) as another floating point number. Hence the API in this case can be interpreted as the collection of the included files used by the C language and its human readable description provided by the main pages.

API in modern languages

Most of the modern programming languages provide the documentation associated to an API in some digital format that makes it easy to consult on a computer. E.g. perl comes with the tool perldoc:

```
$ perldoc -f sqrt
       sqrt EXPR
       sqrt    #Return the square root of EXPR.  If EXPR is omitted,
returns
               #square root of $_.  Only works on non-negative
operands, unless
```

```
                #you've loaded the standard Math::Complex module.
```

python comes with the tool pydoc:

```
$ pydoc math.sqrt
Help on built-in function sqrt in math:
math.sqrt = sqrt(...)
    sqrt(x)
    Return the square root of x.
```

ruby comes with the tool `ri`:

```
$ ri Math::sqrt
-------------------------------------------------------------
Math::sqrt
     Math.sqrt(numeric)    => float
-----------------------------------------------------------------------
-
     Returns the non-negative square root of _numeric_.
```

Java comes with the documentation organized in html pages (JavaDoc format), while Microsoft distributes the API documentation for its languages (Visual C++, C#, Visual Basic, F#, etc...) embedded in Visual Studio help system.

API in object-oriented languages

In object oriented languages, an API usually includes a description of a set of class definitions, with a set of behaviours associated with those classes. A *behaviour* is the set of rules for how an object, derived from that class, will act in a given circumstance. This abstract concept is associated with the real functionalities exposed, or made available, by the classes that are implemented in terms of class methods.

The API in this case can be conceived as the totality of all the methods publicly exposed by the classes (usually called the class *interface*). This means that the API prescribes the methods by which one interacts with/handles the objects derived from the class definitions.

More generally, one can see the API as the collection of all the *kind* of objects one can derive from the class definitions, and their associated possible behaviours. Again: the use is mediated by the public methods, but in this interpretation, the methods are seen as a *technical detail* of how the behaviour is implemented.

For instance: a class representing a `Stack` can simply expose publicly two methods `push()` (to add a new item to the stack), and `pop()` (to extract the last item, ideally placed on top of the stack).

In this case the API can be interpreted as the two methods `pop()` and `push()`, or, more generally, as the *idea* that one can use an item of type `Stack` that implements the behaviour of a stack: a pile *exposing* its top to add/remove elements.

This concept can be carried to the point where a class interface in an API has no methods at all, but only behaviours associated with it. For instance, the Java language API includes the interface `Serializable`, which requires that each class that implements it should behave in a serialized fashion. This does not require to have any public method, but rather requires that any class implements it to have a representation that can be *saved* (serialized) at any time (this is typically true for any class containing simple data and no link to external resources, like an open connection to a file, a remote system, or an external device).

In this sense, in object oriented languages, the API defines a set of behaviors, possibly mediated by a set of class methods.

In such languages, the API is still distributed as a library. For example, the Java language libraries include a set of APIs that are provided in the form of the JDK used by the developers to build new Java programs. The JDK includes the documentation of the API in JavaDoc notation.

The quality of the documentation associated to an API is often a factor determining its success in terms of ease of use.

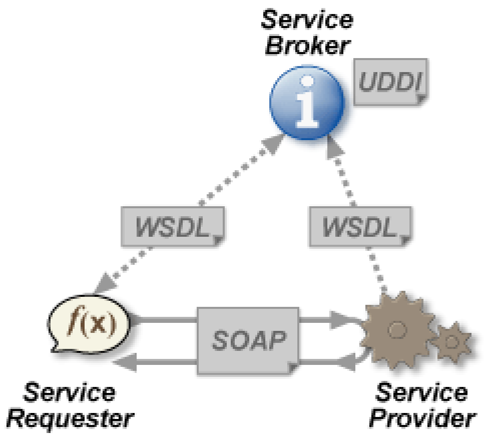
API and protocols

An API can also be an implementation of a protocol.

In general the difference between an API and a protocol is that the protocol defines a standard way to exchange requests and responses based on a common transport, while an API provides a library to be used directly: hence there can be no *transport*, but rather only simple *function calls*.

When an API implements a protocol it can be based on proxy methods for remote invocations that underneath rely on the communication protocol. The role of the API can be exactly to hide the protocol.

Web service



Web services architecture.

A **web service** is typically an application programming interface (API) or **Web API** that is accessed via Hypertext Transfer Protocol (HTTP) and executed on a remote system, hosting the requested service. Web services tend to fall into one of two camps: big web services and RESTful web services.

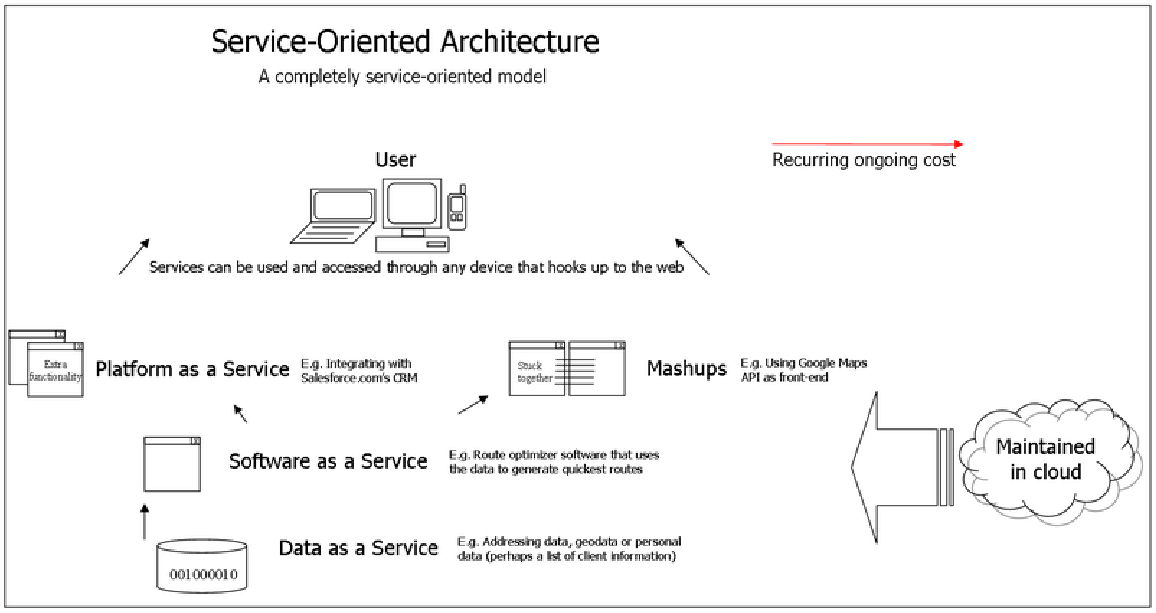
The W3C defines a "web service" as "a software system designed to support interoperable machine-to-machine interaction over a network. It has an interface described in a machine-processable format (specifically Web Services Description Language WSDL). Other systems interact with the web service in a manner prescribed by its description using SOAP messages, typically conveyed using HTTP with an XML serialization in conjunction with other Web-related standards."

The W3C also states, "We can identify two major classes of Web services, REST-compliant Web services, in which the primary purpose of the service is to manipulate XML representations of Web resources using a uniform set of "stateless" operations; and arbitrary Web services, in which the service may expose an arbitrary set of operations."

Big web services

"Big web services" use Extensible Markup Language (XML) messages that follow the SOAP standard and have been popular with traditional enterprise. In such systems, there is often a machine-readable description of the operations offered by the service written in the Web Services Description Language (WSDL). The latter is not a requirement of a SOAP *endpoint*, but it is a prerequisite for automated client-side code generation in many Java and .NET SOAP frameworks (frameworks such as Spring, Apache Axis2 and Apache CXF being notable exceptions). Some industry organizations, such as the WS-I, mandate both SOAP and WSDL in their definition of a web service.

Web API


Service-Oriented Architecture
A completely service-oriented model
User
Recurring ongoing cost
Services can be used and accessed through any device that hooks up to the web
Extra functionality
Platform as a Service
E.g. Integrating with Salesforce.com's CRM
Stuck together
Mashups
E.g. Using Google Maps API as front-end
Software as a Service
E.g. Route optimizer software that uses the data to generate quickest routes
Maintained in cloud
Data as a Service
E.g. Addressing data, geodata or personal data (perhaps a list of client information)
001000010

Web services in a service-oriented architecture.

Web API is a development in web services (in a movement called Web 2.0) where emphasis has been moving away from SOAP based services towards Representational State Transfer (REST) based communications. REST services do not require XML, SOAP, or WSDL service-API definitions.

Web APIs allow the combination of multiple web services into new applications known as mashups.

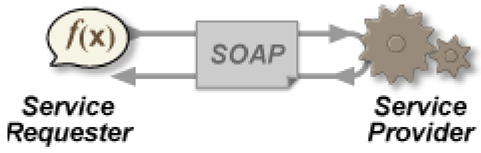
When used in the context of web development, Web API is typically a defined set of Hypertext Transfer Protocol (HTTP) request messages along with a definition of the structure of response messages, usually expressed in an Extensible Markup Language (XML) or JavaScript Object Notation (JSON) format.

When running composite web services, each sub service can be considered autonomous. The user has no control over these services. Also the web services themselves are not reliable; the service provider may remove, change or update their services without giving notice to users. The reliability and fault tolerance is not well supported; faults may happen during the execution. Exception handling in the context of web services is still an open research issue. Still it can be handled by responding with an error object to the client.

Styles of use

Web services are a set of tools that can be used in a number of ways. The three most common styles of use are RPC, SOA and REST.

Remote procedure calls



Architectural elements involved in the XML-RPC.

RPC web services present a distributed function (or method) call interface that is familiar with many developers. Typically, the basic unit of RPC web services is the WSDL operation.

The first web services tools were focused on RPC, and as a result this style is widely deployed and supported. However, it is sometimes criticized for not being loosely coupled, because it was often implemented by mapping services directly to language-specific functions or method calls. Many vendors felt this approach to be a dead end, and pushed for RPC to be disallowed in the WS-I Basic Profile.

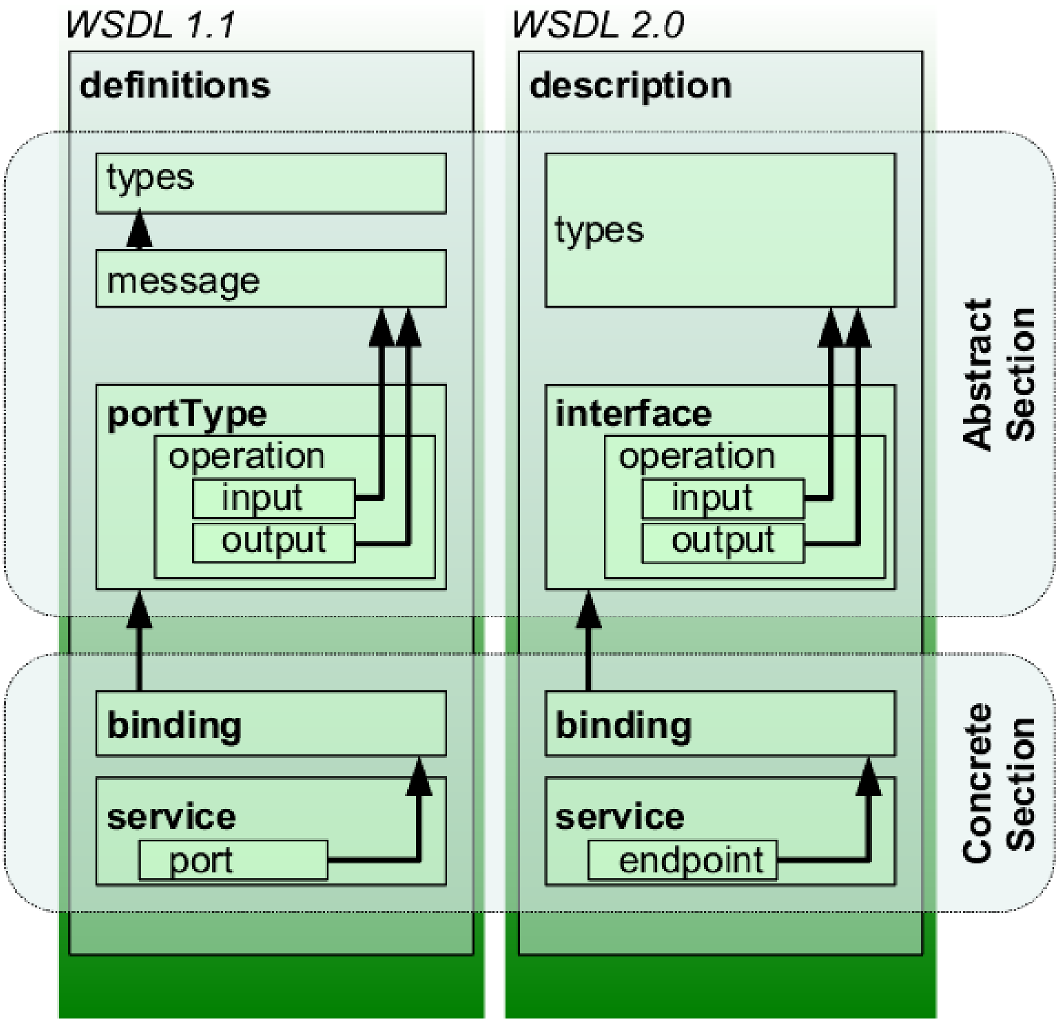
Other approaches with nearly the same functionality as RPC are Object Management Group's (OMG) Common Object Request Broker Architecture (CORBA), Microsoft's Distributed Component Object Model (DCOM) or Sun Microsystems's Java/Remote Method Invocation (RMI).

Service-oriented architecture

Web services can also be used to implement an architecture according to service-oriented architecture (SOA) concepts, where the basic unit of communication is a message, rather than an operation. This is often referred to as "message-oriented" services.

SOA web services are supported by most major software vendors and industry analysts. Unlike RPC web services, loose coupling is more likely, because the focus is on the "contract" that WSDL provides, rather than the underlying implementation details.

Middleware analysts use enterprise service buses which combine message-oriented processing and web services to create an event-driven SOA. One example of an open-source ESB is Mule, another one is Open ESB.



Representation of concepts defined by WSDL 1.1 and WSDL 2.0 documents.

Representational state transfer (REST)

REST attempts to describe architectures which use HTTP or similar protocols by constraining the interface to a set of well-known, standard operations (like GET, POST, PUT, DELETE for HTTP). Here, the focus is on interacting with stateful resources, rather than messages or operations.

An architecture based on REST (one that is 'RESTful') can use WSDL to describe SOAP messaging over HTTP, can be implemented as an abstraction purely on top of SOAP (e.g., WS-Transfer), or can be created without using SOAP at all.

WSDL version 2.0 offers support for binding to all the HTTP request methods (not only GET and POST as in version 1.1) so it enables a better implementation of RESTful Web services. However, support for this specification is still poor in software development kits, which often offer tools only for WSDL 1.1.

Design methodologies

A web service can be written in two ways:

- A developer using the "bottom up method" first writes the implementing class in a programming language, and then uses a WSDL generating tool to expose its methods as a web service. This is often the simpler approach.
- A developer using the "top down method" first writes the WSDL document and then uses a code generating tool to produce the class skeleton, which he or she later completes. This way is generally considered more difficult but can produce cleaner designs

Criticisms

Critics of non-RESTful web services often complain that they are too complex and based upon large software vendors or integrators, rather than typical open source implementations. There are open source implementations like Apache Axis and Apache CXF.

One key concern of the REST web service developers is that the SOAP WS toolkits make it easy to define new interfaces for remote interaction, often relying on introspection to extract the WSDL, since a minor change on the server (even an upgrade of the SOAP stack) can result in different WSDL and a different service interface. The client-side classes that can be generated from WSDL and XSD descriptions of the service are often similarly tied to a particular version of the SOAP endpoint and can break if the endpoint changes or the client-side SOAP stack is upgraded. Well-designed SOAP endpoints (with handwritten XSD and WSDL) do not suffer from this but there is still the problem that a custom interface for every service requires a custom client for every service.

There are also concerns about performance due to web services' use of XML as a message format and SOAP/HTTP in enveloping and transport.

Use of APIs to share content

The practice of publishing APIs has allowed web communities to create an open architecture for sharing content and data between communities and applications. In this way, content that is created in one place can be dynamically posted and updated in multiple locations on the web.

1. Photos can be shared from sites like Flickr and Photobucket to social network sites like Facebook and MySpace.
2. Content can be embedded, e.g. embedding a presentation from SlideShare on a LinkedIn profile.

3. Content can be dynamically posted. Sharing live comments made on Twitter with a Facebook account, for example, is enabled by their APIs.
4. Video content can be embedded on sites which are served by another host.
5. User information can be shared from web communities to outside applications, delivering new functionality to the web community that shares its user data via an open API. One of the best examples of this is the Facebook Application platform. Another is the Open Social platform.

Implementations

The POSIX standard defines an API that allows a wide range of common computing functions to be written in a way such that they may operate on many different systems (Mac OS X, and various Berkeley Software Distributions (BSDs) implement this interface); however, making use of this requires re-compiling for each platform. A compatible API, on the other hand, allows compiled object code to function without any changes to the system implementing that API. This is beneficial to both software providers (where they may distribute existing software on new systems without producing and distributing upgrades) and users (where they may install older software on their new systems without purchasing upgrades), although this generally requires that various software libraries implement the necessary APIs as well.

Microsoft has shown a strong commitment to a backward compatible API, particularly within their Windows API (Win32) library, such that older applications may run on newer versions of Windows using an executable-specific setting called "Compatibility Mode".

Apple Inc. has shown less concern, breaking compatibility or implementing an API in a slower "emulation mode"; this allows greater freedom in development, at the cost of making older software obsolete.

Among Unix-like operating systems, there are many related but incompatible operating systems running on a common hardware platform (particularly Intel 80386-compatible systems). There have been several attempts to standardize the API such that software vendors may distribute one binary application for all these systems; however, to date, none of these have met with much success. The Linux Standard Base is attempting to do this for the Linux platform, while many of the BSD Unixes, such as FreeBSD, NetBSD, and OpenBSD, implement various levels of API compatibility for both backward compatibility (allowing programs written for older versions to run on newer distributions of the system) and cross-platform compatibility (allowing execution of foreign code without recompiling).

Release policies

The two options for releasing API are:

1. Protecting information on APIs from the general public. For example, Sony used to make its official PlayStation 2 API available only to licensed PlayStation developers. This enabled Sony to control who wrote PlayStation 2 games. This gives companies quality control privileges and can provide them with potential licensing revenue streams.
2. Making APIs freely available. For example, Microsoft makes the Microsoft Windows API public, and Apple releases its APIs Carbon and Cocoa, so that software can be written for their platforms.

A mix of the two behaviors can be used as well.

ABIs

The related term application binary interface (ABI) is a lower level definition concerning details at the assembly language level. For example, the Linux Standard Base is an ABI, while POSIX is an API.

API examples

- ASPI for SCSI device interfacing
- Carbon and Cocoa for the Macintosh
- DirectX for Microsoft Windows
- Java APIs
- OpenGL cross-platform graphics API
- OpenAL cross-platform sound API
- OpenCL cross-platform API for general-purpose computing for CPUs & GPUs
- OpenMP API that supports multi-platform shared memory multiprocessing programming in C, C++ and Fortran on many architectures, including Unix and Microsoft Windows platforms.
- Simple DirectMedia Layer (SDL)
- Windows API
- Talend integrates its data management with BPM from Bonita Open Solution

Language bindings and interface generators

APIs that are intended to be used by more than one high-level programming language often provide, or are augmented with, facilities to automatically map the API to features (syntactic or semantic) that are more natural in those languages. This is known as language binding, and is itself an API. The aim is to encapsulate most of the required functionality of the API, leaving a "thin" layer appropriate to each language.

Below are listed some interface generator tools which bind languages to APIs at compile time.

- SWIG opensource interfaces bindings generator from many languages to many languages (Typically Compiled->Scripted)

- F2PY: Fortran to Python interface generator.

Code coverage

Code coverage is a measure used in software testing. It describes the degree to which the source code of a program has been tested. It is a form of testing that inspects the code directly and is therefore a form of white box testing. In time, the use of code coverage has been extended to the field of digital hardware, the contemporary design methodology of which relies on hardware description languages (HDLs).

Code coverage was among the first methods invented for systematic software testing. The first published reference was by Miller and Maloney in *Communications of the ACM* in 1963.

Code coverage is one consideration in the safety certification of avionics equipment. The standard by which avionics gear is certified by the Federal Aviation Administration (FAA) is documented in DO-178B.

Coverage criteria

To measure how well the program is exercised by a test suite, one or more *coverage criteria* are used.

Basic coverage criteria

There are a number of coverage criteria, the main ones being:

- **Function coverage** - Has each function (or subroutine) in the program been called?
- **Statement coverage** - Has each node in the program been executed?
- **Decision coverage** or **branch coverage** - Has every edge in the program been executed? For instance, have the requirements of each branch of each control structure (such as in IF and CASE statements) been met as well as not met?
- **Condition coverage** (or predicate coverage) - Has each boolean sub-expression evaluated both to true and false? This does not necessarily imply decision coverage.
- **Condition/decision coverage** - Both decision and condition coverage should be satisfied.

For example, consider the following C++ function:

```
int foo(int x, int y)
{
    int z = 0;
    if ((x>0) && (y>0)) {
        z = x;
    }
    return z;
}
```

Assume this function is a part of some bigger program and this program was run with some test suite.

- If during this execution function 'foo' was called at least once, then *function coverage* for this function is satisfied.
- *Statement coverage* for this function will be satisfied if it was called e.g. as `foo(1,1)`, as in this case, every line in the function is executed including `z = x;`.
- Tests calling `foo(1,1)` and `foo(1,0)` will satisfy *decision coverage*, as in the first case the `if` condition is satisfied and `z = x;` is executed, and in the second it is not.
- *Condition coverage* can be satisfied with tests that call `foo(1,1)`, `foo(1,0)` and `foo(0,0)`. These are necessary as in the first two cases `(x>0)` evaluates to `true` while in the third it evaluates `false`. At the same time, the first case makes `(y>0)` `true` while the second and third make it `false`.

In languages, like Pascal, where standard boolean operations are not short circuited, condition coverage does not necessarily imply decision coverage. For example, consider the following fragment of code:

```
if a and b then
```

Condition coverage can be satisfied by two tests:

- `a=true`, `b=false`
- `a=false`, `b=true`

However, this set of tests does not satisfy decision coverage as in neither case will the `if` condition be met.

Fault injection may be necessary to ensure that all conditions and branches of exception handling code have adequate coverage during testing.

Modified condition/decision coverage

For safety-critical applications (e.g. for avionics software) it is often required that **modified condition/decision coverage (MC/DC)** is satisifed. This criteria extends condition/decision criteria with requirements that each condition should affect the decision outcome independently. For example, consider the following code:

```
if (a or b) and c then
```

The condition/decision criteria will be satisfied by the following set of tests:

- a=true, b=true, c=true
- a=false, b=false, c=false

However, the above tests set will not satisfy modified condition/decision coverage, since in the first test, the value of 'b' and in the second test the value of 'c' would not influence the output. So, the following test set is needed to satisfy MC/DC:

- a=false, b=true, c=true
- a=true, b=false, c=true
- a=true, b=true, c=false

Multiple condition coverage

This criteria requires that all combinations of conditions inside each decision are tested. For example, the code fragment from the previous section will require eight tests:

- a=false, b=false, c=false
- a=false, b=false, c=true
- a=false, b=true, c=false
- a=false, b=true, c=true
- a=true, b=false, c=false
- a=true, b=false, c=true
- a=true, b=true, c=false
- a=true, b=true, c=true

Other coverage criteria

There are further coverage criteria, which are used less often:

- **Linear Code Sequence and Jump (LCSAJ) coverage** - has every LCSAJ been executed?
- **JJ-Path coverage** - have all jump to jump paths (aka LCSAJs) been executed?
- **Path coverage** - Has every possible route through a given part of the code been executed?
- **Entry/exit coverage** - Has every possible call and return of the function been executed?
- **Loop coverage** - Has every possible loop been executed zero times, once, and more than once?

Safety-critical applications are often required to demonstrate that testing achieves 100% of some form of code coverage.

Some of the coverage criteria above are connected. For instance, path coverage implies decision, statement and entry/exit coverage. Decision coverage implies statement coverage, because every statement is part of a branch.

Full path coverage, of the type described above, is usually impractical or impossible. Any module with a succession of n decisions in it can have up to 2^n paths within it; loop constructs can result in an infinite number of paths. Many paths may also be infeasible, in that there is no input to the program under test that can cause that particular path to be executed. However, a general-purpose algorithm for identifying infeasible paths has been proven to be impossible (such an algorithm could be used to solve the halting problem). Methods for practical path coverage testing instead attempt to identify classes of code paths that differ only in the number of loop executions, and to achieve "basis path" coverage the tester must cover all the path classes.

In practice

The target software is built with special options or libraries and/or run under a special environment such that every function that is exercised (executed) in the program(s) is mapped back to the function points in the source code. This process allows developers and quality assurance personnel to look for parts of a system that are rarely or never accessed under normal conditions (error handling and the like) and helps reassure test engineers that the most important conditions (function points) have been tested. The resulting output is then analyzed to see what areas of code have not been exercised and the tests are updated to include these areas as necessary. Combined with other code coverage methods, the aim is to develop a rigorous, yet manageable, set of regression tests.

In implementing code coverage policies within a software development environment one must consider the following:

- What are coverage requirements for the end product certification and if so what level of code coverage is required? The typical level of rigor progression is as follows: Statement, Branch/Decision, Modified Condition/Decision Coverage(MC/DC), LCSAJ (Linear Code Sequence and Jump)
- Will code coverage be measured against tests that verify requirements levied on the system under test (DO-178B)?
- Is the object code generated directly traceable to source code statements? Certain certifications, (ie. DO-178B Level A) require coverage at the assembly level if this is not the case: "Then, additional verification should be performed on the object code to establish the correctness of such generated code sequences" (DO-178B) para-6.4.4.2.

Test engineers can look at code coverage test results to help them devise test cases and input or configuration sets that will increase the code coverage over vital functions. Two common forms of code coverage used by testers are statement (or line) coverage and path (or edge) coverage. Line coverage reports on the execution footprint of testing in terms of which lines of code were executed to complete the test. Edge coverage reports which branches or code decision points were executed to complete the test. They both report a coverage metric, measured as a percentage. The meaning of this depends on what form(s) of code coverage have been used, as 67% path coverage is more comprehensive than 67% statement coverage.

Generally, code coverage tools and libraries exact a performance and/or memory or other resource cost which is unacceptable to normal operations of the software. Thus, they are only used in the lab. As one might expect, there are classes of software that cannot be feasibly subjected to these coverage tests, though a degree of coverage mapping can be approximated through analysis rather than direct testing.

There are also some sorts of defects which are affected by such tools. In particular, some race conditions or similar real time sensitive operations can be masked when run under code coverage environments; and conversely, some of these defects may become easier to find as a result of the additional overhead of the testing code.

Chapter 3

Fault Injection and Mutation Testing

Fault injection

In software testing, **fault injection** is a technique for improving the coverage of a test by introducing faults to test code paths, in particular error handling code paths, that might otherwise rarely be followed. It is often used with stress testing and is widely considered to be an important part of developing robust software. Robustness testing (also known as Syntax Testing, Fuzzing or Fuzz testing) is a type of fault injection commonly used to test for vulnerabilities in communication interfaces such as protocols, command line parameters, or APIs.

The propagation of a fault through to an observable failure follows a well defined cycle. When executed, a fault may cause an error, which is an invalid state within a system boundary. An error may cause further errors within the system boundary, therefore each new error acts as a fault, or it may propagate to the system boundary and be observable. When error states are observed at the system boundary they are termed failures. This mechanism is termed the fault-error-failure cycle and is a key mechanism in dependability.

History

The technique of fault injection dates back to the 1970s when it was first used to induce faults at a hardware level. This type of fault injection is called Hardware Implemented Fault Injection (HWIFI) and attempts to simulate hardware failures within a system. The first experiments in hardware fault injection involved nothing more than shorting connections on circuit boards and observing the effect on the system (bridging faults). It was used primarily as a test of the dependability of the hardware system. Later specialised hardware was developed to extend this technique, such as devices to bombard specific areas of a circuit board with heavy radiation. It was soon found that faults could be induced by software techniques and that aspects of this technique could be useful for assessing software systems. Collectively these techniques are known as Software Implemented Fault Injection (SWIFI).

Software Implemented fault injection

SWIFI techniques for software fault injection can be categorized into two types: compile-time injection and runtime injection.

Compile-time injection is an injection technique where source code is modified to inject simulated faults into a system. One method is called mutation testing which changes existing lines of code so that they contain faults. A simple example of this technique could be changing

```
a = a + 1
  to
a = a – 1
```

Code mutation produces faults which are very similar to those unintentionally added by programmers.

A refinement of code mutation is *Code Insertion Fault Injection* which adds code, rather than modifies existing code. This is usually done through the use of perturbation functions which are simple functions which take an existing value and perturb it via some logic into another value, for example

```
int pFunc(int value) {
  return value + 20;
}
int main(int argc, char * argv[]) {
  int a = pFunc(aFunction(atoi(argv)));
  if (a > 20) {
    /* do something */
  } else {
    /* do something else */
  }
}
```

In this case pFunc is the perturbation function and it is applied to the return value of the function that has been called introducing a fault into the system.

Runtime Injection techniques use a software trigger to inject a fault into a running software system. Faults can be injected via a number of physical methods and triggers can be implemented in a number of ways, such as: Time Based triggers (When the timer reaches a specified time an interrupt is generated and the interrupt handler associated with the timer can inject the fault.); Interrupt Based Triggers (Hardware exceptions and software trap mechanisms are used to generate an interrupt at a specific place in the system code or on a particular event within the system, for instance access to a specific memory location).

Runtime injection techniques can use a number of different techniques to insert faults into a system via a trigger.

- Corruption of memory space: This technique consists of corrupting RAM, processor registers, and I/O map.
- Syscall interposition techniques: This is concerned with the fault propagation from operating system kernel interfaces to executing systems software. This is done by intercepting operating system calls made by user-level software and injecting faults into them.
- Network Level fault injection: This technique is concerned with the corruption, loss or reordering of network packets at the network interface.

These techniques are often based around the debugging facilities provided by computer processor architectures.

Protocol software fault injection

Complex software systems, especially multi-vendor distributed systems based on open standards, perform input/output operations to exchange data via stateful, structured exchanges known as "protocols." One kind of fault injection that is particularly useful to test protocol implementations (a type of software code that has the unusual characteristic in that it cannot predict or control its input) is fuzzing. Fuzzing is an especially useful form of Black-box testing since the various invalid inputs that are submitted to the software system do not depend on, and are not created based on knowledge of, the details of the code running inside the system.

Fault injection tools

Although these types of faults can be injected by hand the possibility of introducing an unintended fault is high, so tools exist to parse a program automatically and insert faults.

Research tools

A number of SWIFI Tools have been developed and a selection of these tools is given here. Six commonly used fault injection tools are Ferrari, FTAPE , Doctor, Orchestra, Xception and Grid-FIT.

- Ferrari (Fault and Error Automatic Real-Time Injection) is based around software traps that inject errors into a system. The traps are activated by either a call to a specific memory location or a timeout. When a trap is called the handler injects a fault into the system. The faults can either be transient or permanent. Research conducted with Ferrari shows that error detection is dependent on the fault type and where the fault is inserted .
- FTAPE (Fault Tolerance and Performance Evaluator) can inject faults, not only into memory and registers, but into disk accesses as well. This is achieved by inserting a special disk driver into the system that can inject faults into data sent

and received from the disk unit. FTAPE also has a synthetic load unit that can simulate specific amounts of load for robustness testing purposes .

- DOCTOR (IntegrateD SOftware Fault InjeCTiOn EnviRonment) allows injection of memory and register faults, as well as network communication faults. It uses a combination of time-out, trap and code modification. Time-out triggers inject transient memory faults and traps inject transient emulated hardware failures, such as register corruption. Code modification is used to inject permanent faults .
- Orchestra is a script driven fault injector which is based around Network Level Fault Injection. Its primary use is the evaluation and validation of the fault-tolerance and timing characteristics of distributed protocols. Orchestra was initially developed for the Mach Operating System and uses certain features of this platform to compensate for latencies introduced by the fault injector. It has also been successfully ported to other operating systems.
- Xception is designed to take advantage of the advanced debugging features available on many modern processors. It is written to require no modification of system source and no insertion of software traps, since the processor's exception handling capabilities trigger fault injection. These triggers are based around accesses to specific memory locations. Such accesses could be either for data or fetching instructions. It is therefore possible to accurately reproduce test runs because triggers can be tied to specific events, instead of timeouts .
- Grid-FIT (Grid – Fault Injection Technology) is a dependability assessment method and tool for assessing Grid services by fault injection. Grid-FIT is derived from an earlier fault injector WS-FIT which was targeted towards Java Web Services implemented using Apache Axis transport. Grid-FIT utilises a novel fault injection mechanism that allows network level fault injection to be used to give a level of control similar to Code Insertion fault injection whilst being less invasive .
- LFI (Library-level Fault Injector) is an automatic testing tool suite, used to simulate in a controlled testing environment, exceptional situations that programs need to handle at runtime but that are not easy to check via input testing alone. LFI automatically identifies the errors exposed by shared libraries, finds potentially buggy error recovery code in program binaries and injects the desired faults at the boundary between shared libraries and applications.

Commercial tools

- ExhaustiF is a commercial software tool used for grey box testing based on software fault injection (SWIFI) to improve reliability of software intensive systems. The tool can be used during system integration and system testing phases of any software development lifecycle, complementing other testing tools as well. ExhaustiF is able to inject faults into both software and hardware. When injecting simulated faults in software, ExhaustiF offers the following fault types: Variable Corruption and Procedure Corruption. The catalogue for hardware fault injections includes faults in Memory (I/O, RAM) and CPU (Integer Unit, Floating Unit). There are different versions available for RTEMS/ERC32, RTEMS/Pentium, Linux/Pentium and MS-Windows/Pentium.

- Holodeck is a test tool developed by Security Innovation that uses fault injection to simulate real-world application and system errors for Windows applications and services. Holodeck customers include many major commercial software development companies, including Microsoft, Symantec, EMC and Adobe. It provides a controlled, repeatable environment in which to analyze and debug error-handling code and application attack surfaces for fragility and security testing. It simulates file and network fuzzing faults as well as a wide range of other resource, system and custom-defined faults. It analyzes code and recommends test plans and also performs function call logging, API interception, stress testing, code coverage analysis and many other application security assurance functions.

- Codenomicon Defensics is a blackbox test automation framework that does fault injection to more than 150 different interfaces including network protocols, API interfaces, files, and XML structures. The commercial product was launched in 2001, after five years of research at University of Oulu in the area of software fault injection. A thesis work explaining the used fuzzing principles was published by VTT, one of the PROTOS consortium members.

- The Mu Service Analyzer is a commercial service testing tool developed by Mu Dynamics. The Mu Service Analyzer performs black box and white box testing of services based on their exposed software interfaces, using denial-of-service simulations, service-level traffic variations (to generate invalid inputs) and the replay of known vulnerability triggers. All these techniques exercise input validation and error handling and are used in conjunction with valid protocol monitors and SNMP to characterize the effects of the test traffic on the software system. The Mu Service Analyzer allows users to establish and track system-level reliability, availability and security metrics for any exposed protocol implementation. The tool has been available in the market since 2005 by customers in the North America, Asia and Europe, especially in the critical markets of network operators (and their vendors) and Industrial control systems (including Critical infrastructure).

- Xception is a commercial software tool developed by Critical Software SA used for black box and white box testing based on software fault injection (SWIFI) and Scan Chain fault injection (SCIFI). Xception allows users to test the robustness of their systems or just part of them, allowing both Software fault injection and Hardware fault injection for a specific set of architectures. The tool has been used in the market since 1999 and has customers in the American, Asian and European markets, especially in the critical market of aerospace and the telecom market. The full Xception product family includes: a) The main Xception tool, a state-of-the-art leader in Software Implemented Fault Injection (SWIFI) technology; b) The Easy Fault Definition (EFD) and Xtract (Xception Analysis Tool) add-on tools; c) The extended Xception tool (eXception), with the fault injection extensions for Scan Chain and pin-level forcing.

Libraries

- TestApi is a shared-source API library, which provides facilities for fault injection testing as well as other testing types, data-structures and algorithms for .NET applications.

Application of fault injection

Fault injection can take many forms. In the testing of operating systems for example, fault injection is often performed by a *driver* (kernel-mode software) that intercepts *system calls* (calls into the kernel) and randomly returning a failure for some of the calls. This type of fault injection is useful for testing low level user mode software. For higher level software, various methods inject faults. In managed code, it is common to use instrumentation. Although fault injection can be undertaken by hand a number of fault injection tools exist to automate the process of fault injection .

Depending on the complexity of the API for the level where faults are injected, fault injection tests often must be carefully designed to minimise the number of false positives. Even a well designed fault injection test can sometimes produce situations that are impossible in the normal operation of the software. For example, imagine there are two API functions, `Commit` and `PrepareForCommit`, such that alone, each of these functions can possibly fail, but if `PrepareForCommit` is called and succeeds, a subsequent call to `Commit` is guaranteed to succeed. Now consider the following code:

```
error = PrepareForCommit();
if (error == SUCCESS) {
  error = Commit();
  assert(error == SUCCESS);
}
```

Often, it will be infeasible for the fault injection implementation to keep track of enough state to make the guarantee that the API functions make. In this example, a fault injection test of the above code might hit the assert, whereas this would never happen in normal operation.

Mutation testing

Mutation testing (or *Mutation analysis* or *Program mutation*) is a method of software testing, which involves modifying programs' source code or byte code in small ways. In short, any tests which pass after code has been mutated are considered defective. These so-called *mutations*, are based on well-defined *mutation operators* that either mimic typical programming errors (such as using the wrong operator or variable name) or force the creation of valuable tests (such as driving each expression to zero). The purpose is to help the tester develop effective tests or locate weaknesses in the test data used for the program or in sections of the code that are seldom or never accessed during execution.

Tests can be created to verify the correctness of the implementation of a given software system. But the creation of tests still poses the question whether the tests are correct and sufficiently cover the requirements that have originated the implementation. (This technological problem is itself an instance of a deeper philosophical problem named "Quis custodiet ipsos custodes?" ["Who will guard the guards?"].) In this context, mutation testing was pioneered in the 1970s to locate and expose weaknesses in test suites. The theory was that if a mutation was introduced without the behavior (generally output) of the program being affected, this indicated either that the code that had been mutated was never executed (redundant code) or that the testing suite was unable to locate the injected fault. In order for this to function at any scale, a large number of mutations had to be introduced into a large program, leading to the compilation and execution of an extremely large number of copies of the program. This problem of the expense of mutation testing had reduced its practical use as a method of software testing, but the increased use of object oriented programming languages and unit testing frameworks has led to the creation of mutation testing tools for many programming languages as a means to test individual portions of an application.

Mutation testing was originally proposed by Richard Lipton as a student in 1971, and first developed and published by DeMillo, Lipton and Sayward. The first implementation of a mutation testing tool was by Timothy Budd as part of his PhD work (titled *Mutation Analysis*) in 1980 from Yale University.

Recently, with the availability of massive computing power, there has been a resurgence of mutation analysis within the computer science community, and work has been done to define methods of applying mutation testing to object oriented programming languages and non-procedural languages such as XML, SMV, and finite state machines.

In 2004 a company called Certess Inc. extended many of the principles into the hardware verification domain. Whereas mutation analysis only expects to detect a difference in the output produced, Certess extends this by verifying that a checker in the testbench will actually detect the difference. This extension means that all three stages of verification, namely: activation, propagation and detection are evaluated. They have called this functional qualification.

Fuzzing is a special area of mutation testing. In fuzzing, the messages or data exchanged inside communication interfaces (both inside and between software instances) are mutated, in order to catch failures or differences in processing the data. Codenomicon (2001) and Mu Dynamics (2005) evolved fuzzing concepts to a fully stateful mutation testing platform, complete with monitors for thoroughly exercising protocol implementations.

Mutation testing overview

Mutation testing is done by selecting a set of mutation operators and then applying them to the source program one at a time for each applicable piece of the source code. The result of applying one mutation operator to the program is called a *mutant*. If the test suite is able to detect the change (i.e. one of the tests fails), then the mutant is said to be *killed*.

For example, consider the following C++ code fragment:

```
if (a && b)
    c = 1;
else
    c = 0;
```

The condition mutation operator would replace '&&' with '||' and produce the following mutant:

```
if (a || b)
    c = 1;
else
    c = 0;
```

Now, for the test to kill this mutant, the following condition should be met:

- Test input data should cause different program states for the mutant and the original program. For example, a test with a=1 and b=0 would do this.
- The value of 'c' should be propagated to the program's output and checked by the test.

Weak mutation testing (or *weak mutation coverage*) requires that only the first condition is satisfied. *Strong mutation testing* requires that both conditions are satisfied. Strong mutation is more powerful, since it ensures that the test suite can really catch the problems. Weak mutation is closely related to code coverage methods. It requires much less computing power to ensure that the test suite satisfies weak mutation testing than strong mutation testing.

Equivalent mutants

Many mutation operators can produce equivalent mutants. For example, consider the following code fragment:

```
int index=0;
while (...)
{
    . . .;
    index++;
    if (index==10)
        break;
}
```

Boolean relation mutation operator will replace "==" with ">=" and produce the following mutant:

```
int index=0;
while (...)
{
    . . .;
    index++;
    if (index>=10)
        break;
}
```

However, it is not possible to find a test case which could kill this mutant. The resulting program is equivalent to the original one. Such mutants are called *equivalent mutants*.

Equivalent mutants detection is one of biggest obstacles for practical usage of mutation testing. The effort, needed to check if mutants are equivalent or not, can be very high even for small programs.

Mutation operators

A variety of mutation operators were explored by researchers. Here are some examples of mutation operators for imperative languages:

- Statement deletion.
- Replace each boolean subexpression with *true* and *false*.
- Replace each arithmetic operation with another one, e.g. + with *, - and /.
- Replace each boolean relation with another one, e.g. > with >=, == and <=.
- Replace each variable with another variable declared in the same scope (variable types should be the same).

These mutation operators are also called traditional mutation operators. Beside this, there are mutation operators for object-oriented languages , for concurrent constructions, complex objects like containers etc. They are called class-level mutation operators. For example the MuJava tool offers various class-level mutation operators such as: Access Modifier Change, Type Cast Operator Insertion, Type Cast Operator Deletion. Moreover, mutation operators have been developed to perform security vulnerability testing of programs

Chapter 4

Exploratory Testing, Fuzz Testing and Equivalence Partitioning

Exploratory testing

Exploratory testing is an approach to software testing that is concisely described as simultaneous learning, test design and test execution. Cem Kaner, who coined the term in 1983, now defines exploratory testing as "a style of software testing that emphasizes the personal freedom and responsibility of the individual tester to continually optimize the quality of his/her work by treating test-related learning, test design, test execution, and test result interpretation as mutually supportive activities that run in parallel throughout the project."

While the software is being tested, the tester learns things that together with experience and creativity generates new good tests to run. Exploratory testing is often thought of as a black box testing technique. Instead, those who have studied it consider it a test *approach* that can be applied to any test technique, at any stage in the development process. The key is not the test technique nor the item being tested or reviewed; the key is the cognitive engagement of the tester, and the tester's responsibility for managing his or her time.

History

Exploratory testing has always been performed by skilled testers. In the early 1990s, ad hoc was too often synonymous with sloppy and careless work. As a result, a group of test methodologists (now calling themselves the Context-Driven School) began using the term "exploratory" seeking to emphasize the dominant thought process involved in unscripted testing, and to begin to develop the practice into a teachable discipline. This new terminology was first published by Cem Kaner in his book *Testing Computer Software* and expanded upon in *Lessons Learned in Software Testing*. Exploratory testing can be as disciplined as any other intellectual activity.

Description

Exploratory testing seeks to find out how the software actually works, and to ask questions about how it will handle difficult and easy cases. The quality of the testing is dependent on the tester's skill of inventing test cases and finding defects. The more the tester knows about the product and different test methods, the better the testing will be.

To further explain, comparison can be made of freestyle exploratory testing to its antithesis scripted testing. In this activity test cases are designed in advance. This includes both the individual steps and the expected results. These tests are later performed by a tester who compares the actual result with the expected. When performing exploratory testing, expectations are open. Some results may be predicted and expected; others may not. The tester configures, operates, observes, and evaluates the product and its behaviour, critically investigating the result, and reporting information that seems like to be a bug (which threatens the value of the product to some person) or an issue (which threatens the quality of the testing effort).

In reality, testing almost always is a combination of exploratory and scripted testing, but with a tendency towards either one, depending on context.

According to Cem Kaner & James Bach, exploratory testing is more a mindset or "...a way of thinking about testing" than a methodology. They also say that it crosses a continuum from slightly exploratory (slightly ambiguous or vaguely scripted testing) to highly exploratory (freestyle exploratory testing).

The documentation of exploratory testing ranges from documenting all tests performed to just documenting the bugs. During pair testing, two persons create test cases together; one performs them, and the other documents. Session-based testing is a method specifically designed to make exploratory testing auditable and measurable on a wider scale.

Exploratory testers often use tools, including screen capture or video tools as a record of the exploratory session, or tools to quickly help generate situations of interest, e.g. James Bach's Perlclip.

Benefits and drawbacks

The main advantage of exploratory testing is that less preparation is needed, important bugs are found quickly, and at execution time, the approach tends to be more intellectually stimulating than execution of scripted tests.

Another major benefit is that testers can use deductive reasoning based on the results of previous results to guide their future testing on the fly. They do not have to complete a current series of scripted tests before focusing in on or moving on to exploring a more target rich environment. This also accelerates bug detection when used intelligently.

Another benefit is that, after initial testing, most bugs are discovered by some sort of exploratory testing. This can be demonstrated logically by stating, "Programs that pass certain tests tend to continue to pass the same tests and are more likely to fail other tests or scenarios that are yet to be explored."

Disadvantages are that tests invented and performed on the fly can't be reviewed in advance (and by that prevent errors in code and test cases), and that it can be difficult to show exactly which tests have been run.

Freestyle exploratory test ideas, when revisited, are unlikely to be performed in exactly the same manner, which can be an advantage if it is important to find new errors; or a disadvantage if it is more important to repeat specific details of the earlier tests. This can be controlled with specific instruction to the tester, or by preparing automated tests where feasible, appropriate, and necessary, and ideally as close to the unit level as possible.

Usage

Exploratory testing is particularly suitable if requirements and specifications are incomplete, or if there is lack of time. The approach can also be used to verify that previous testing has found the most important defects.

Fuzz testing

Fuzz testing or **fuzzing** is a software testing technique that provides invalid, unexpected, or random data to the inputs of a program. If the program fails (for example, by crashing or failing built-in code assertions), the defects can be noted.

The term Fuzz originated from a class project topic in Prof. Barton Miller's graduate Advanced Operating System class at the University of Wisconsin in the Fall of 1988. The assignment was titled "Operating System Utility Program Reliability - The Fuzz Generator". In quality assurance and testing, the same approach (using unexpected data or syntax) has been called robustness testing, syntax testing or negative testing. Even white-noise testing can be thought of as fuzzing.

File formats and network protocols are the most common targets of fuzz testing, but any type of program input can be fuzzed. Interesting inputs include environment variables, keyboard and mouse events, and sequences of API calls. Even items not normally considered "input" can be fuzzed, such as the contents of databases, shared memory, or the precise interleaving of threads.

For the purpose of security, input that crosses a trust boundary is often the most interesting. For example, it is more important to fuzz code that handles the upload of a file by any user than it is to fuzz the code that parses a configuration file that is accessible only to a privileged user.

Uses

Fuzz testing is often used in large software development projects that employ black-box testing. These projects usually have a budget to develop test tools, and fuzz testing is one of the techniques which offers a high benefit to cost ratio.

However, fuzz testing is not a substitute for exhaustive testing or formal methods: it can only provide a random sample of the system's behavior, and in many cases passing a fuzz test may only demonstrate that a piece of software can handle exceptions without crashing, rather than behaving correctly. Thus, fuzz testing can only be regarded as an assurance of overall quality rather than a bug-finding tool.

As a gross measurement of reliability, fuzzing can suggest which parts of a program should get special attention, in the form of a code audit, application of static analysis, or partial rewrites.

Techniques

The simplest form of fuzzing technique is sending a stream of random bits to software, either as command line options, randomly mutated protocol packets, or as events. The oldest folklore on testing similar to fuzzing tells about The Monkey, from before 1983, which used journaling hooks to feed random events to Macintosh applications. The first command line fuzzer originated from Prof. Barton Miller's group at the University of Wisconsin in 1988. This technique of random inputs still continues to be a powerful tool to find bugs in command-line applications, network protocols, and GUI-based applications and services. Another common technique that is easy to implement is mutating existing input (e.g. files from a test suite) by flipping bits at random or moving blocks of the file around. However, the most successful fuzzers have detailed understanding of the format or protocol being tested.

The understanding can be based on a specification. A specification-based fuzzer involves writing the entire array of specifications into the tool, and then using model-based test generation techniques in walking through the specifications and adding anomalies in the data contents, structures, messages, and sequences. This "smart fuzzing" technique is also known as robustness testing, syntax testing, grammar testing, and (input) fault injection. The protocol awareness can also be created heuristically from examples using a tool such as Sequitur. These fuzzers can *generate* test cases from scratch, or they can *mutate* examples from test suites or real life. They can concentrate on *valid* or *invalid* input, with *mostly-valid* input tending to trigger the "deepest" error cases.

There are two limitations of protocol-based fuzzing based on protocol implementations of published specifications: 1) Testing cannot proceed until the specification is relatively mature, since a specification is a prerequisite for writing such a fuzzer; and 2) Many useful protocols are proprietary, or involve proprietary extensions to published protocols. If fuzzing is based only on published specifications, test coverage for new or proprietary protocols will be limited or nonexistent.

Fuzz testing can be combined with other testing techniques. **White-box fuzzing** uses symbolic execution and constraint solving. **Evolutionary fuzzing** leverages feedback from code coverage, effectively automating the approach of *exploratory testing*.

Types of bugs found

Straight-up failures such as crashes, assertion failures, and memory leaks are easy to detect. The use of a memory debugger can help find bugs too subtle to always crash.

Fuzz testing is especially useful against large applications, where any bug affecting memory safety is likely to be a severe vulnerability. It is these security concerns that motivate the development of most fuzzers.

Since fuzzing often generates invalid input, it is especially good at testing error-handling routines, which are important for software that does not control its input. As such, simple fuzzing can be thought of as a way to automate negative testing. More sophisticated fuzzing tests more "main-line" code, along with error paths deep within it.

Fuzzing can also find some types of "correctness" bugs. For example, it can be used to find incorrect-serialization bugs by complaining whenever a program's serializer emits something that the same program's parser rejects. It can also find unintentional differences between two versions of a program or between two implementations of the same specification.

Reproduction and isolation

As a practical matter, developers need to reproduce errors in order to fix them. For this reason, almost all fuzz testing makes a record of the data it manufactures, usually before applying it to the software, so that if the computer fails dramatically, the test data is preserved. If the fuzz stream is pseudo-random number generated it may be easier to store the seed value to reproduce the fuzz attempt.

Once a bug found through fuzzing is reproduced, it is often desirable to produce a simple test case to make the issue easier to understand and debug. A simple testcase may also be faster and therefore more suitable for inclusion in a test suite that is run frequently. It can even help to hide the way in which the bug was found. Some fuzzers are designed to work well with testcase reduction programs such as Delta or Lithium.

Advantages and disadvantages

The main problem with fuzzing to find program faults is that it generally only finds very simple faults. The computational complexity of the software testing problem is of exponential order ($O(c^n),\ c > 1$) and every fuzzer takes shortcuts to find something interesting in a timeframe that a human cares about. A primitive fuzzer may have poor code coverage; for example, if the input includes a checksum which is not properly updated to match other random changes, only the checksum validation code will be verified. Code coverage tools are often used to estimate how "well" a fuzzer works, but these are only guidelines to fuzzer quality. Every fuzzer can be expected to find a different set of bugs.

On the other hand, bugs found using fuzz testing are sometimes severe, exploitable bugs that could be used by a real attacker. This has become more common as fuzz testing has become more widely known, as the same techniques and tools are now used by attackers to exploit deployed software. This is a major advantage over binary or source auditing, or even fuzzing's close cousin, fault injection, which often relies on artificial fault conditions that are difficult or impossible to exploit.

The randomness of inputs used in fuzzing is often seen as a disadvantage, as catching a boundary value condition with random inputs is highly unlikely.

Fuzz testing enhances software security and software safety because it often finds odd oversights and defects which human testers would fail to find, and even careful human test designers would fail to create tests for.

Frameworks

- Powerfuzzer - GPLv3, Python. Fuzz test HTTP targets.
- OWASP JBroFuzz - web server/web application fuzz tester.
- Sulley - GPLv2, Python. Fuzz targets unclear.
- Peach Fuzzing Platform - C# .NET. File/network fuzzer.
- SPIKE - GPL, C. Linux only, focuses on network protocol fuzzing. Lots of examples, but unmaintained since 2004.
- Evolutionary Fuzzing System- GPLv2, Python. Aims to discover protocols automatically based on feedback from fuzz target.
- Tarantula - MIT, Ruby. Fuzz tests Ruby on Rails applications.

Equivalence partitioning

Equivalence partitioning is a software testing technique that divides the input data of a software unit into partitions of data from which test cases can be derived. In principle, test cases are designed to cover each partition at least once. This technique tries to define test cases that uncover classes of errors, thereby reducing the total number of test cases that must be developed.

In rare cases equivalence partitioning is also applied to outputs of a software component, typically it is applied to the inputs of a tested component. The equivalence partitions are usually derived from the requirements specification for input attributes that influence the processing of the test object. An input has certain ranges which are valid and other ranges which are invalid. Invalid data here does not mean that the data is incorrect, it means that this data lies outside of specific partition. This may be best explained by the example of a function which takes a parameter "month". The valid range for the month is 1 to 12, representing January to December. This valid range is called a partition. In this example there are two further partitions of invalid ranges. The first invalid partition would be <= 0 and the second invalid partition would be >= 13.

```
        ... -2 -1  0 1 .............. 12 13  14  15 .....
      --------------|-------------------|---------------------
 invalid partition 1     valid partition    invalid partition 2
```

The testing theory related to equivalence partitioning says that only one test case of each partition is needed to evaluate the behaviour of the program for the related partition. In other words it is sufficient to select one test case out of each partition to check the behaviour of the program. To use more or even all test cases of a partition will not find new faults in the program. The values within one partition are considered to be "equivalent". Thus the number of test cases can be reduced considerably.

An additional effect of applying this technique is that you also find the so called "dirty" test cases. An inexperienced tester may be tempted to use as test cases the input data 1 to 12 for the month and forget to select some out of the invalid partitions. This would lead to a huge number of unnecessary test cases on the one hand, and a lack of test cases for the dirty ranges on the other hand.

The tendency is to relate equivalence partitioning to so called black box testing which is strictly checking a software component at its interface, without consideration of internal structures of the software. But having a closer look at the subject there are cases where it applies to grey box testing as well. Imagine an interface to a component which has a valid range between 1 and 12 like the example above. However internally the function may have a differentiation of values between 1 and 6 and the values between 7 and 12. Depending upon the input value the software internally will run through different paths to perform slightly different actions. Regarding the input and output interfaces to the component this difference will not be noticed, however in your grey-box testing you would like to make sure that both paths are examined. To achieve this it is necessary to introduce additional equivalence partitions which would not be needed for black-box testing. For this example this would be:

```
        ... -2 -1  0 1 ..... 6 7 ..... 12 13  14  15 .....
      --------------|---------|----------|---------------------
 invalid partition 1      P1         P2     invalid partition 2
                       valid partitions
```

To check for the expected results you would need to evaluate some internal intermediate values rather than the output interface. It is not necessary that we should use multiple values from each partition. In the above scenario we can take -2 from invalid partition 1, 6 from valid partition, and 15 from invalid partition 2.

Equivalence partitioning is not a stand alone method to determine test cases. It has to be supplemented by boundary value analysis. Having determined the partitions of possible inputs the method of boundary value analysis has to be applied to select the most effective test cases out of these partitions.

Chapter 5

Unit Testing and Integration Testing

Unit testing

In computer programming, **unit testing** is a method by which individual units of source code are tested to determine if they are fit for use. A unit is the smallest testable part of an application. In procedural programming a unit may be an individual function or procedure. Unit tests are created by programmers or occasionally by white box testers.

Ideally, each test case is independent from the others: substitutes like method stubs, mock objects, fakes and test harnesses can be used to assist testing a module in isolation. Unit tests are typically written and run by software developers to ensure that code meets its design and behaves as intended. Its implementation can vary from being very manual (pencil and paper) to being formalized as part of build automation.

Benefits

The goal of unit testing is to isolate each part of the program and show that the individual parts are correct. A unit test provides a strict, written contract that the piece of code must satisfy. As a result, it affords several benefits. Unit tests find problems early in the development cycle.

Facilitates change

Unit testing allows the programmer to refactor code at a later date, and make sure the module still works correctly (e.g., in regression testing). The procedure is to write test cases for all functions and methods so that whenever a change causes a fault, it can be quickly identified and fixed.

Readily-available unit tests make it easy for the programmer to check whether a piece of code is still working properly.

In continuous unit testing environments, through the inherent practice of sustained maintenance, unit tests will continue to accurately reflect the intended use of the executable and code in the face of any change. Depending upon established development practices and unit test coverage, up-to-the-second accuracy can be maintained.

Simplifies integration

Unit testing may reduce uncertainty in the units themselves and can be used in a bottom-up testing style approach. By testing the parts of a program first and then testing the sum of its parts, integration testing becomes much easier.

An elaborate hierarchy of unit tests does not equal integration testing. Integration with peripheral units should be included in integration tests, but not in unit tests. Integration testing cannot be fully automated and thus still relies heavily on human testers.

Documentation

Unit testing provides a sort of living documentation of the system. Developers looking to learn what functionality is provided by a unit and how to use it can look at the unit tests to gain a basic understanding of the unit's API.

Unit test cases embody characteristics that are critical to the success of the unit. These characteristics can indicate appropriate/inappropriate use of a unit as well as negative behaviors that are to be trapped by the unit. A unit test case, in and of itself, documents these critical characteristics, although many software development environments do not rely solely upon code to document the product in development.

By contrast, ordinary narrative documentation is more susceptible to drifting from the implementation of the program and will thus become outdated (e.g., design changes, feature creep, relaxed practices in keeping documents up-to-date).

Design

When software is developed using a test-driven approach, the unit test may take the place of formal design. Each unit test can be seen as a design element specifying classes, methods, and observable behaviour. The following Java example will help illustrate this point.

Here is a test class that specifies a number of elements of the implementation. First, that there must be an interface called Adder, and an implementing class with a zero-argument constructor called AdderImpl. It goes on to assert that the Adder interface should have a method called add, with two integer parameters, which returns another integer. It also specifies the behaviour of this method for a small range of values.

```
public class TestAdder {
    public void testSum() {
        Adder adder = new AdderImpl();
        assert(adder.add(1, 1) == 2);
        assert(adder.add(1, 2) == 3);
        assert(adder.add(2, 2) == 4);
        assert(adder.add(0, 0) == 0);
        assert(adder.add(-1, -2) == -3);
        assert(adder.add(-1, 1) == 0);
        assert(adder.add(1234, 988) == 2222);
    }
}
```

In this case the unit test, having been written first, acts as a design document specifying the form and behaviour of a desired solution, but not the implementation details, which are left for the programmer. Following the "do the simplest thing that could possibly work" practice, the easiest solution that will make the test pass is shown below.

```
interface Adder {
    int add(int a, int b);
}
class AdderImpl implements Adder {
    int add(int a, int b) {
        return a + b;
    }
}
```

Unlike other diagram-based design methods, using a unit-test as a design has one significant advantage. The design document (the unit-test itself) can be used to verify that the implementation adheres to the design. With the unit-test design method, the tests will never pass if the developer does not implement the solution according to the design.

It is true that unit testing lacks some of the accessibility of a diagram, but UML diagrams are now easily generated for most modern languages by free tools (usually available as extensions to IDEs). Free tools, like those based on the xUnit framework, outsource to another system the graphical rendering of a view for human consumption.

Separation of interface from implementation

Because some classes may have references to other classes, testing a class can frequently spill over into testing another class. A common example of this is classes that depend on a database: in order to test the class, the tester often writes code that interacts with the database. This is a mistake, because a unit test should usually not go outside of its own class boundary, and especially should not cross such process/network boundaries because this can introduce unacceptable performance problems to the unit test-suite. Crossing such unit boundaries turns unit tests into integration tests, and when test cases fail, makes it less clear which component is causing the failure.

Instead, the software developer should create an abstract interface around the database queries, and then implement that interface with their own mock object. By abstracting this necessary attachment from the code (temporarily reducing the net effective coupling), the independent unit can be more thoroughly tested than may have been previously achieved. This results in a higher quality unit that is also more maintainable.

Unit testing limitations

Testing cannot be expected to catch every error in the program: it is impossible to evaluate every execution path in all but the most trivial programs. The same is true for unit testing. Additionally, unit testing by definition only tests the functionality of the units themselves. Therefore, it will not catch integration errors or broader system-level errors (such as functions performed across multiple units, or non-functional test areas such as performance). Unit testing should be done in conjunction with other software testing activities. Like all forms of software testing, unit tests can only show the presence of errors; they cannot show the absence of errors.

Software testing is a combinatorial problem. For example, every boolean decision statement requires at least two tests: one with an outcome of "true" and one with an outcome of "false". As a result, for every line of code written, programmers often need 3 to 5 lines of test code. This obviously takes time and its investment may not be worth the effort. There are also many problems that cannot easily be tested at all – for example those that are nondeterministic or involve multiple threads. In addition, writing code for a unit test is as likely to be at least as buggy as the code it is testing. Fred Brooks in The Mythical Man-Month quotes: *never take two chronometers to sea. Always take one or three.* Meaning, if two chronometers contradict, how do you know which one is correct?

To obtain the intended benefits from unit testing, rigorous discipline is needed throughout the software development process. It is essential to keep careful records not only of the tests that have been performed, but also of all changes that have been made to the source code of this or any other unit in the software. Use of a version control system is essential. If a later version of the unit fails a particular test that it had previously passed, the version-control software can provide a list of the source code changes (if any) that have been applied to the unit since that time.

It is also essential to implement a sustainable process for ensuring that test case failures are reviewed daily and addressed immediately. If such a process is not implemented and ingrained into the team's workflow, the application will evolve out of sync with the unit test suite, increasing false positives and reducing the effectiveness of the test suite.

Applications

Extreme Programming

Unit testing is the cornerstone of Extreme Programming, which relies on an automated unit testing framework. This automated unit testing framework can be either third party, e.g., xUnit, or created within the development group.

Extreme Programming uses the creation of unit tests for test-driven development. The developer writes a unit test that exposes either a software requirement or a defect. This test will fail because either the requirement isn't implemented yet, or because it intentionally exposes a defect in the existing code. Then, the developer writes the simplest code to make the test, along with other tests, pass.

Most code in a system is unit tested, but not necessarily all paths through the code. Extreme Programming mandates a "test everything that can possibly break" strategy, over the traditional "test every execution path" method. This leads developers to develop fewer tests than classical methods, but this isn't really a problem, more a restatement of fact, as classical methods have rarely ever been followed methodically enough for all execution paths to have been thoroughly tested. Extreme Programming simply recognizes that testing is rarely exhaustive (because it is often too expensive and time-consuming to be economically viable) and provides guidance on how to effectively focus limited resources.

Crucially, the test code is considered a first class project artifact in that it is maintained at the same quality as the implementation code, with all duplication removed. Developers release unit testing code to the code repository in conjunction with the code it tests. Extreme Programming's thorough unit testing allows the benefits mentioned above, such as simpler and more confident code development and refactoring, simplified code integration, accurate documentation, and more modular designs. These unit tests are also constantly run as a form of regression test.

Techniques

Unit testing is commonly automated, but may still be performed manually. The IEEE does not favor one over the other. A manual approach to unit testing may employ a step-by-step instructional document. Nevertheless, the objective in unit testing is to isolate a unit and validate its correctness. Automation is efficient for achieving this, and enables the many benefits listed here. Conversely, if not planned carefully, a careless manual unit test case may execute as an integration test case that involves many software components, and thus preclude the achievement of most if not all of the goals established for unit testing.

To fully realize the effect of isolation while using an automated approach, the unit or code body under test is executed within a framework outside of its natural environment. In other words, it is executed outside of the product or calling context for which it was originally created. Testing in such an isolated manner reveals unnecessary dependencies between the code being tested and other units or data spaces in the product. These dependencies can then be eliminated.

Using an automation framework, the developer codes criteria into the test to verify the unit's correctness. During test case execution, the framework logs tests that fail any criterion. Many frameworks will also automatically flag these failed test cases and report them in a summary. Depending upon the severity of a failure, the framework may halt subsequent testing.

As a consequence, unit testing is traditionally a motivator for programmers to create decoupled and cohesive code bodies. This practice promotes healthy habits in software development. Design patterns, unit testing, and refactoring often work together so that the best solution may emerge.

Unit testing frameworks

Unit testing frameworks are most often third-party products that are not distributed as part of the compiler suite. They help simplify the process of unit testing, having been developed for a wide variety of languages. Some examples of frameworks are XUnit, and PHPUnit.

It is generally possible to perform unit testing without the support of a specific framework by writing client code that exercises the units under test and uses assertions, exception handling, or other control flow mechanisms to signal failure. Unit testing without a framework is valuable in that there is a barrier to entry for the adoption of unit testing; having scant unit tests is hardly better than having none at all, whereas once a framework is in place, adding unit tests becomes relatively easy. In some frameworks many advanced unit test features are missing or must be hand-coded.

Language-level unit testing support

Some programming languages support unit testing directly (Eg. Java). Their grammar allows the direct declaration of unit tests without importing a library (whether third party or standard). Additionally, the boolean conditions of the unit tests can be expressed in the same syntax as boolean expressions used in non-unit test code, such as what is used for `if` and `while` statements.

Languages that directly support unit testing include:

- Cobra
- D

Integration testing

Integration testing (sometimes called Integration and Testing, abbreviated "I&T") is the phase in software testing in which individual software modules are combined and tested as a group. It occurs after unit testing and before system testing. Integration testing takes as its input modules that have been unit tested, groups them in larger aggregates, applies tests defined in an integration test plan to those aggregates, and delivers as its output the integrated system ready for system testing.

Purpose

The purpose of integration testing is to verify functional, performance, and reliability requirements placed on major design items. These "design items", i.e. assemblages (or groups of units), are exercised through their interfaces using Black box testing, success and error cases being simulated via appropriate parameter and data inputs. Simulated usage of shared data areas and inter-process communication is tested and individual subsystems are exercised through their input interface. Test cases are constructed to test that all components within assemblages interact correctly, for example across procedure calls or process activations, and this is done after testing individual modules, i.e. unit testing. The overall idea is a "building block" approach, in which verified assemblages are added to a verified base which is then used to support the integration testing of further assemblages.

Some different types of integration testing are big bang, top-down, and bottom-up.

Big Bang

In this approach, all or most of the developed modules are coupled together to form a complete software system or major part of the system and then used for integration testing. The Big Bang method is very effective for saving time in the integration testing process. However, if the test cases and their results are not recorded properly, the entire integration process will be more complicated and may prevent the testing team from achieving the goal of integration testing.

A type of Big Bang Integration testing is called **Usage Model testing**. Usage Model testing can be used in both software and hardware integration testing. The basis behind this type of integration testing is to run user-like workloads in integrated user-like environments. In doing the testing in this manner, the environment is proofed, while the individual components are proofed indirectly through their use. Usage Model testing takes an optimistic approach to testing, because it expects to have few problems with the individual components. The strategy relies heavily on the component developers to do the isolated unit testing for their product. The goal of the strategy is to avoid redoing the testing done by the developers, and instead flesh out problems caused by the interaction of the components in the environment. For integration testing, Usage Model testing can be more efficient and provides better test coverage than traditional focused functional integration testing. To be more efficient and accurate, care must be used in defining the user-like workloads for creating realistic scenarios in exercising the environment. This gives that the integrated environment will work as expected for the target customers.

Top-down and Bottom-up

Bottom Up Testing is an approach to integrated testing where the lowest level components are tested first, then used to facilitate the testing of higher level components. The process is repeated until the component at the top of the hierarchy is tested.

All the bottom or low-level modules, procedures or functions are integrated and then tested. After the integration testing of lower level integrated modules, the next level of modules will be formed and can be used for integration testing. This approach is helpful only when all or most of the modules of the same development level are ready. This method also helps to determine the levels of software developed and makes it easier to report testing progress in the form of a percentage.

Top Down Testing is an approach to integrated testing where the top integrated modules are tested and the branch of the module is tested step by step until the end of the related module.

Sandwich Testing is an approach to combine top down testing with bottom up testing.

The main advantage of the Bottom-Up approach is that bugs are more easily found. With Top-Down, it is easier to find a missing branch link.

Limitations

Any conditions not stated in specified integration tests, outside of the confirmation of the execution of design items, will generally not be tested.

Chapter 6

GUI Software Testing and Software Performance Testing

GUI software testing

In computer science, **GUI software testing** is the process of testing a product that uses a graphical user interface, to ensure it meets its written specifications. This is normally done through the use of a variety of test cases.

Test Case Generation

To generate a ‘good’ set of test cases, the test designers must be certain that their suite covers all the functionality of the system and also has to be sure that the suite fully exercises the GUI itself. The difficulty in accomplishing this task is twofold: one has to deal with domain size and then one has to deal with sequences. In addition, the tester faces more difficulty when they have to do regression testing.

The size problem can be easily illustrated. Unlike a CLI (command line interface) system, a GUI has many operations that need to be tested. A very small program such as Microsoft WordPad has 325 possible GUI operations. In a large program, the number of operations can easily be an order of magnitude larger.

The second problem is the sequencing problem. Some functionality of the system may only be accomplishable by following some complex sequence of GUI events. For example, to open a file a user may have to click on the File Menu and then select the Open operation, and then use a dialog box to specify the file name, and then focus the application on the newly opened window. Obviously, increasing the number of possible operations increases the sequencing problem exponentially. This can become a serious issue when the tester is creating test cases manually.

Regression testing becomes a problem with GUIs as well. This is because the GUI may change significantly across versions of the application, even though the underlying application may not. A test designed to follow a certain path through the GUI may not be able to follow that path since a button, menu item, or dialog may have changed location or appearance.

These issues have driven the GUI testing problem domain towards automation. Many different techniques have been proposed to automatically generate test suites that are complete and that simulate user behavior.

Most of the techniques used to test GUIs attempt to build on techniques previously used to test CLI programs. However, most of these have scaling problems when they are applied to GUI's. For example, Finite State Machine-based modeling — where a system is modeled as a finite state machine and a program is used to generate test cases that exercise all states — can work well on a system that has a limited number of states but may become overly complex and unwieldy for a GUI.

Planning and artificial intelligence

A novel approach to test suite generation, adapted from a **CLI** technique involves using a planning system. Planning is a well-studied technique from the artificial intelligence (AI) domain that attempts to solve problems that involve four parameters:

- an initial state,
- a goal state,
- a set of operators, and
- a set of objects to operate on.

Planning systems determine a path from the initial state to the goal state by using the operators. An extremely simple planning problem would be one where you had two words and one operation called 'change a letter' that allowed you to change one letter in a word to another letter – the goal of the problem would be to change one word into another.

For GUI testing, the problem is a bit more complex. In the authors used a planner called IPP to demonstrate this technique. The method used is very simple to understand. First, the systems UI is analyzed to determine what operations are possible. These operations become the operators used in the planning problem. Next an initial system state is determined. Next a goal state is determined that the tester feels would allow exercising of the system. Lastly the planning system is used to determine a path from the initial state to the goal state. This path becomes the test plan.

Using a planner to generate the test cases has some specific advantages over manual generation. A planning system, by its very nature, generates solutions to planning problems in a way that is very beneficial to the tester:

1. The plans are always valid. What this means is that the output of the system can be one of two things, a valid and correct plan that uses the operators to attain the goal state or no plan at all. This is beneficial because much time can be wasted when manually creating a test suite due to invalid test cases that the tester thought would work but didn't.

2. A planning system pays attention to order. Often to test a certain function, the test case must be complex and follow a path through the GUI where the operations are performed in a specific order. When done manually, this can lead to errors and also can be quite difficult and time consuming to do.
3. Finally, and most importantly, a planning system is goal oriented. What this means and what makes this fact so important is that the tester is focusing test suite generation on what is most important, testing the functionality of the system.

When manually creating a test suite, the tester is more focused on how to test a function (i. e. the specific path through the GUI). By using a planning system, the path is taken care of and the tester can focus on what function to test. An additional benefit of this is that a planning system is not restricted in any way when generating the path and may often find a path that was never anticipated by the tester. This problem is a very important one to combat.

Another interesting method of generating GUI test cases uses the theory that good GUI test coverage can be attained by simulating a novice user. One can speculate that an expert user of a system will follow a very direct and predictable path through a GUI and a novice user would follow a more random path. The theory therefore is that if we used an expert to test the GUI, many possible system states would never be achieved. A novice user, however, would follow a much more varied, meandering and unexpected path to achieve the same goal so it's therefore more desirable to create test suites that simulate novice usage because they will test more.

The difficulty lies in generating test suites that simulate 'novice' system usage. Using Genetic algorithms is one proposed way to solve this problem. Novice paths through the system are not random paths. First, a novice user will learn over time and generally won't make the same mistakes repeatedly, and, secondly, a novice user is not analogous to a group of monkeys trying to type Hamlet, but someone who is following a plan and probably has some domain or system knowledge.

Genetic algorithms work as follows: a set of 'genes' are created randomly and then are subjected to some task. The genes that complete the task best are kept and the ones that don't are discarded. The process is again repeated with the surviving genes being replicated and the rest of the set filled in with more random genes. Eventually one gene (or a small set of genes if there is some threshold set) will be the only gene in the set and is naturally the best fit for the given problem.

For the purposes of the GUI testing, the method works as follows. Each gene is essentially a list of random integer values of some fixed length. Each of these genes represents a path through the GUI. For example, for a given tree of widgets, the first value in the gene (each value is called an allele) would select the widget to operate on, the following alleles would then fill in input to the widget depending on the number of possible inputs to the widget (for example a pull down list box would have one input…the selected list value). The success of the genes are scored by a criterion that rewards the best 'novice' behavior.

The system to do this testing described in can be extended to any windowing system but is described on the X window system. The X Window system provides functionality (via XServer and the editors' protocol) to dynamically send GUI input to and get GUI output from the program without directly using the GUI. For example, one can call XSendEvent() to simulate a click on a pull-down menu, and so forth. This system allows researchers to automate the gene creation and testing so for any given application under test, a set of novice user test cases can be created.

Event Flow Graphs

A 2007 development in the field of automated GUI testing is a new graph model called the event-flow graph that represents events and event interactions. In much the same way as a control-flow graph represents all possible execution paths in a program, and a data-flow graph represents all possible definitions and uses of a memory location, the event-flow model represents all possible sequences of events that can be executed on the GUI. A GUI is decomposed into a hierarchy of modal dialogues; this hierarchy is represented as an integration tree; each modal dialogue is represented as an event-flow graph that shows all possible event execution paths in the dialogue.

Running the test cases

At first the strategies were migrated and adapted from the CLI testing strategies. A popular method used in the CLI environment is capture/playback. Capture playback is a system where the system screen is “captured” as a bitmapped graphic at various times during system testing. This capturing allowed the tester to “play back” the testing process and compare the screens at the output phase of the test with expected screens. This validation could be automated since the screens would be identical if the case passed and different if the case failed.

Using capture/playback worked quite well in the CLI world but there are significant problems when one tries to implement it on a GUI-based system . The most obvious problem one finds is that the screen in a GUI system may look different while the state of the underlying system is the same, making automated validation extremely difficult. This is because a GUI allows graphical objects to vary in appearance and placement on the screen. Fonts may be different, window colors or sizes may vary but the system output is basically the same. This would be obvious to a user, but not obvious to an automated validation system.

To combat this and other problems, testers have gone ‘under the hood’ and collected GUI interaction data from the underlying windowing system . By capturing the window ‘events’ into logs the interactions with the system are now in a format that is decoupled from the appearance of the GUI. Now, only the event streams are captured. There is some filtering of the event streams necessary since the streams of events are usually very detailed and most events aren’t directly relevant to the problem. This approach can be made easier by using an MVC architecture for example and making the view (i. e. the GUI here) as simple as possible while the model and the controller hold all the logic.

Another approach is to use the software's built-in assistive technology, to use an HTML interface or a three-tier architecture that makes it also possible to better separate the user interface from the rest of the application.

Another way to run tests on a GUI is to build a driver into the GUI so that commands or events can be sent to the software from another program. This method of directly sending events to and receiving events from a system is highly desirable when testing, since the input and output testing can be fully automated and user error is eliminated.

Software performance testing

In software engineering, **performance testing** is testing that is performed, to determine how fast some aspect of a system performs under a particular workload. It can also serve to validate and verify other quality attributes of the system, such as scalability, reliability and resource usage.

Performance testing is a subset of Performance engineering, an emerging computer science practice which strives to build performance into the design and architecture of a system, prior to the onset of actual coding effort.

Performance Testing Sub-Genres

Load Testing

Load testing is the simplest form of performance testing. A load test is usually conducted to understand the behavior of the application under a specific expected load. This load can be the expected concurrent number of users on the application performing a specific number of transactions within the set duration. This test will give out the response times of all the important business critical transactions. If the database, application server, etc. are also monitored, then this simple test can itself point towards any bottlenecks in the application software.

Stress Testing

Stress testing is normally used to understand the upper limits of capacity within the application landscape. This kind of test is done to determine the application's robustness in terms of extreme load and helps application administrators to determine if the application will perform sufficiently if the current load goes well above the expected maximum.

Endurance Testing (Soak Testing)

Endurance testing is usually done to determine if the application can sustain the continuous expected load. During endurance tests, memory utilization is monitored to detect potential leaks. Also important, but often overlooked is performance degradation. That is, to ensure that the throughput and/or response times after some long period of sustained activity are as good or better than at the beginning of the test.

Spike Testing

Spike testing, as the name suggests is done by spiking the number of users and understanding the behavior of the application; whether performance will suffer, the application will fail, or it will be able to handle dramatic changes in load.

Configuration Testing

Configuration testing is another variation on traditional performance testing. Rather than testing for performance from the perspective of load you are testing the effects of configuration changes in the application landscape on application performance and behaviour. A common example would be experimenting with different methods of load-balancing.

Isolation Testing

Isolation testing is unique to performance testing but a term used to describe repeating a test execution that resulted in an application problem. Often used to isolate and confirm the fault domain.

Setting performance goals

Performance testing can serve different purposes.

- It can demonstrate that the system meets performance criteria.
- It can compare two systems to find which performs better.
- Or it can measure what parts of the system or workload causes the system to perform badly.

Many performance tests are undertaken without due consideration to the setting of realistic performance goals. The first question from a business perspective should always be "why are we performance testing?". These considerations are part of the business case of the testing. Performance goals will differ depending on the application technology and purpose however they should always include some of the following:-

Concurrency / Throughput

If an application identifies end-users by some form of login procedure then a concurrency goal is highly desirable. By definition this is the largest number of concurrent application users that the application is expected to support at any given moment. The work-flow of your scripted transaction may impact true application concurrency especially if the iterative part contains the Login & Logout activity

If your application has no concept of end-users then your performance goal is likely to be based on a maximum throughput or transaction rate. A common example would be casual browsing of a web site.

Server response time

This refers to the time taken for one application node to respond to the request of another. A simple example would be a HTTP 'GET' request from browser client to web server. In terms of response time this is what all load testing tools actually measure. It may be relevant to set server response time goals between all nodes of the application landscape.

Render response time

A difficult thing for load testing tools to deal with as they generally have no concept of what happens within a node apart from recognising a period of time where there is no activity 'on the wire'. To measure render response time it is generally necessary to include functional test scripts as part of the performance test scenario which is a feature not offered by many load testing tools.

Performance specifications

It is critical to detail performance specifications (requirements) and document them in any performance test plan. Ideally, this is done during the requirements development phase of any system development project, prior to any design effort.

However, **performance testing** is frequently not performed against a specification i.e. no one will have expressed what the maximum acceptable response time for a given population of users should be. Performance testing is frequently used as part of the process of performance profile tuning. The idea is to identify the "weakest link" – there is inevitably a part of the system which, if it is made to respond faster, will result in the overall system running faster. It is sometimes a difficult task to identify which part of the system represents this critical path, and some test tools include (or can have add-ons that provide) instrumentation that runs on the server (agents) and report transaction times, database access times, network overhead, and other server monitors, which can be analyzed together with the raw performance statistics. Without such instrumentation one might have to have someone crouched over Windows Task Manager at the server to see how much CPU load the performance tests are generating (assuming a Windows system is under test).

There is an apocryphal story of a company that spent a large amount optimizing their software without having performed a proper analysis of the problem. They ended up rewriting the system’s ‘idle loop’, where they had found the system spent most of its time, but even having the most efficient idle loop in the world obviously didn’t improve overall performance one iota!

Performance testing can be performed across the web, and even done in different parts of the country, since it is known that the response times of the internet itself vary regionally. It can also be done in-house, although routers would then need to be configured to introduce the lag what would typically occur on public networks. Loads should be introduced to the system from realistic points. For example, if 50% of a system's user base will be accessing the system via a 56K modem connection and the other half over a T1, then the load injectors (computers that simulate real users) should either inject load over the same connections (ideal) or simulate the network latency of such connections, following the same user profile.

It is always helpful to have a statement of the likely peak numbers of users that might be expected to use the system at peak times. If there can also be a statement of what constitutes the maximum allowable 95 percentile response time, then an injector configuration could be used to test whether the proposed system met that specification.

Questions to ask

Performance specifications should ask the following questions, at a minimum:

- In detail, what is the performance test scope? What subsystems, interfaces, components, etc. are in and out of scope for this test?
- For the user interfaces (UI's) involved, how many concurrent users are expected for each (specify peak vs. nominal)?
- What does the target system (hardware) look like (specify all server and network appliance configurations)?
- What is the Application Workload Mix of each application component? (for example: 20% login, 40% search, 30% item select, 10% checkout).
- What is the System Workload Mix? [Multiple workloads may be simulated in a single performance test] (for example: 30% Workload A, 20% Workload B, 50% Workload C)
- What are the time requirements for any/all backend batch processes (specify peak vs. nominal)?

Pre-requisites for Performance Testing

A stable build of the application which must resemble the Production environment as close to possible.

The performance testing environment should not be clubbed with User acceptance testing (UAT) or development environment. This is dangerous as if an UAT or Integration test or other tests are going on in the same environment, then the results obtained from the performance testing may not be reliable. As a best practice it is always advisable to have a separate performance testing environment resembling the production environment as much as possible.

Test conditions

In performance testing, it is often crucial (and often difficult to arrange) for the test conditions to be similar to the expected actual use. This is, however, not entirely possible in actual practice. The reason is that the workloads of production systems have a random nature, and while the test workloads do their best to mimic what may happen in the production environment, it is impossible to exactly replicate this workload variability - except in the most simple system.

Loosely-coupled architectural implementations (e.g.: SOA) have created additional complexities with performance testing. Enterprise services or assets (that share a common infrastructure or platform) require coordinated performance testing (with all consumers creating production-like transaction volumes and load on shared infrastructures or platforms) to truly replicate production-like states. Due to the complexity and financial and time requirements around this activity, some organizations now employ tools that can monitor and create production-like conditions (also referred as "noise") in their performance testing environments (PTE) to understand capacity and resource requirements and verify / validate quality attributes.

Timing

It is critical to the cost performance of a new system, that performance test efforts begin at the inception of the development project and extend through to deployment. The later a performance defect is detected, the higher the cost of remediation. This is true in the case of functional testing, but even more so with performance testing, due to the end-to-end nature of its scope.

Tools

In the diagnostic case, software engineers use tools such as profilers to measure what parts of a device or software contributes most to the poor performance or to establish throughput levels (and thresholds) for maintained acceptable response time.

Myths of Performance Testing

Some of the very common myths are given below.
1. Performance Testing is done to break the system.

Stress Testing is done to understand the break point of the system. Otherwise normal load testing is generally done to understand the behavior of the application under the expected user load. Depending on other requirements, such as expectation of spike load, continued load for an extended period of time would demand spike, endurance soak or stress testing.

2. Performance Testing should only be done after the System Integration Testing

Although this is mostly the norm in the industry, performance testing can also be done while the initial development of the application is taking place. This kind of approach is known as the **Early Performance Testing**. This approach would ensure a holistic development of the application keeping the performance parameters in mind. Thus the finding of a performance bug just before the release of the application and the cost involved in rectifying the bug is reduced to a great extent.

3. Performance Testing only involves creation of scripts and any application changes would cause a simple refactoring of the scripts.

Performance Testing in itself is an evolving science in the Software Industry. Scripting itself although important, is only one of the components of the performance testing. The major challenge for any performance tester is to determine the type of tests needed to execute and analyzing the various performance counters to determine the performance bottleneck.

The other segment of the myth concerning the change in application would result only in little refactoring in the scripts is also untrue as any form of change on the UI especially in the Web protocol would entail complete re-development of the scripts from scratch. This problem becomes bigger if the protocols involved include Web Services, Siebel, Web Click n Script, Citrix, SAP.

Technology

Performance testing technology employs one or more PCs or Unix servers to act as injectors – each emulating the presence of numbers of users and each running an automated sequence of interactions (recorded as a script, or as a series of scripts to emulate different types of user interaction) with the host whose performance is being tested. Usually, a separate PC acts as a test conductor, coordinating and gathering metrics from each of the injectors and collating performance data for reporting purposes. The usual sequence is to ramp up the load – starting with a small number of virtual users and increasing the number over a period to some maximum. The test result shows how the performance varies with the load, given as number of users vs response time. Various tools, are available to perform such tests. Tools in this category usually execute a suite of tests which will emulate real users against the system. Sometimes the results can reveal oddities, e.g., that while the average response time might be acceptable, there are outliers of a few key transactions that take considerably longer to complete – something that might be caused by inefficient database queries, pictures etc.

Performance testing can be combined with stress testing, in order to see what happens when an acceptable load is exceeded –does the system crash? How long does it take to recover if a large load is reduced? Does it fail in a way that causes collateral damage?

Analytical Performance Modeling is a method to model the behaviour of an application in a spreadsheet. The model is fed with measurements of transaction resource demands (CPU, disk I/O, LAN, WAN), weighted by the transaction-mix (business transactions per hour). The weighted transaction resource demands are added-up to obtain the hourly resource demands and divided by the hourly resource capacity to obtain the resource loads. Using the responsetime formula (R=S/(1-U), R=responsetime, S=servicetime, U=load), responsetimes can be calculated and calibrated with the results of the performance tests. Analytical performance modelling allows evaluation of design options and system sizing based on actual or anticipated business usage. It is therefore much faster and cheaper than performance testing, though it requires thorough understanding of the hardware platforms.

Tasks to undertake

Tasks to perform such a test would include:

- Decide whether to use internal or external resources to perform the tests, depending on inhouse expertise (or lack thereof)
- Gather or elicit performance requirements (specifications) from users and/or business analysts
- Develop a high-level plan (or project charter), including requirements, resources, timelines and milestones
- Develop a detailed performance test plan (including detailed scenarios and test cases, workloads, environment info, etc.)
- Choose test tool(s)
- Specify test data needed and charter effort (often overlooked, but often the death of a valid performance test)
- Develop proof-of-concept scripts for each application/component under test, using chosen test tools and strategies
- Develop detailed performance test project plan, including all dependencies and associated timelines
- Install and configure injectors/controller
- Configure the test environment (ideally identical hardware to the production platform), router configuration, quiet network (we don't want results upset by other users), deployment of server instrumentation, database test sets developed, etc.
- Execute tests – probably repeatedly (iteratively) in order to see whether any unaccounted for factor might affect the results
- Analyze the results - either pass/fail, or investigation of critical path and recommendation of corrective action

Chapter 7

Regression Testing and Acceptance Testing

Regression testing

Regression testing is any type of software testing that seeks to uncover software errors after changes to the program (e.g. bugfixes or new functionality) have been made, by retesting the program. The intent of regression testing is to assure that a change, such as a bugfix, did not introduce new bugs. Regression testing can be used to test the system efficiently by systematically selecting the appropriate minimum suite of tests needed to adequately cover the affected change. *Common methods* of regression testing include rerunning previously run tests and checking whether program behavior has changed and whether previously fixed faults have re-emerged. "One of the main reasons for regression testing is that it's often extremely difficult for a programmer to figure out how a change in one part of the software will echo in other parts of the software." This is done by comparing results of previous tests to results of the current tests being run.

Background

Experience has shown that as software is fixed, emergence of new and/or reemergence of old faults is quite common. Sometimes reemergence occurs because a fix gets lost through poor revision control practices (or simple human error in revision control). Often, a fix for a problem will be "fragile" in that it fixes the problem in the narrow case where it was first observed but not in more general cases which may arise over the lifetime of the software. Frequently, a fix for a problem in one area inadvertently causes a software bug in another area. Finally, it is often the case that when some feature is redesigned, some of the same mistakes that were made in the original implementation of the feature were made in the redesign.

Therefore, in most software development situations it is considered good practice that when a bug is located and fixed, a test that exposes the bug is recorded and regularly retested after subsequent changes to the program. Although this may be done through manual testing procedures using programming techniques, it is often done using automated testing tools. Such a test suite contains software tools that allow the testing environment to execute all the regression test cases automatically; some projects even set up automated systems to automatically re-run all regression tests at specified intervals and report any failures (which could imply a regression or an out-of-date test). Common strategies are to run such a system after every successful compile (for small projects), every night, or once a week. Those strategies can be automated by an external tool, such as BuildBot or Hudson.

Regression testing is an integral part of the extreme programming software development method. In this method, design documents are replaced by extensive, repeatable, and automated testing of the entire software package at every stage in the software development cycle.

In the corporate world, regression testing has traditionally been performed by a software quality assurance team after the development team has completed work. However, defects found at this stage are the most costly to fix. This problem is being addressed by the rise of unit testing. Although developers have always written test cases as part of the development cycle, these test cases have generally been either functional tests or unit tests that verify only intended outcomes. Developer testing compels a developer to focus on unit testing and to include both positive and negative test cases.

Uses

Regression testing can be used not only for testing the *correctness* of a program, but often also for tracking the quality of its output. For instance, in the design of a compiler, regression testing could track the code size, simulation time and time of the test suite cases.

Regression testing should be part of a test plan. Regression testing can be automated.

"Also as a consequence of the introduction of new bugs, program maintenance requires far more system testing per statement written than any other programming. Theoretically, after each fix one must run the entire batch of test cases previously run against the system, to ensure that it has not been damaged in an obscure way. In practice, such *regression testing* must indeed approximate this theoretical idea, and it is very costly."

– Fred Brooks, The Mythical Man Month, p 122

Regression tests can be broadly categorized as functional tests or unit tests. Functional tests exercise the complete program with various inputs. Unit tests exercise individual functions, subroutines, or object methods. Both functional testing tools and unit testing tools tend to be third party products that are not part of the compiler suite, and both tend to be automated. Functional tests may be a scripted series of program inputs, possibly even an automated mechanism for controlling mouse movements. Unit tests may be separate functions within the code itself, or driver layer that links to the code without altering the code being tested.

Acceptance testing

In engineering and its various subdisciplines, **acceptance testing** is black-box testing performed on a system (for example: a piece of software, lots of manufactured mechanical parts, or batches of chemical products) prior to its delivery. It is also known as functional testing, black-box testing, QA testing, application testing, confidence testing, final testing, validation testing, or factory acceptance testing.

Software developers often distinguish acceptance testing by the system provider from acceptance testing by the customer (the user or client) prior to accepting transfer of ownership. In the case of software, acceptance testing performed by the customer is known as user acceptance testing (UAT), end-user testing, site (acceptance) testing, or field (acceptance) testing.

A smoke test is used as an acceptance test prior to introducing a build to the main testing process.

Overview

Acceptance testing generally involves running a suite of tests on the completed system. Each individual test, known as a case, exercises a particular operating condition of the user's environment or feature of the system, and will result in a pass or fail, or boolean, outcome. There is generally no degree of success or failure. The test environment is usually designed to be identical, or as close as possible, to the anticipated user's environment, including extremes of such. These test cases must each be accompanied by test case input data or a formal description of the operational activities (or both) to be performed—intended to thoroughly exercise the specific case—and a formal description of the expected results.

Acceptance Tests/Criteria (in Agile Software Development) are usually created by business customers and expressed in a business domain language. These are high-level tests to test the completeness of a user story or stories 'played' during any sprint/iteration. These tests are created ideally through collaboration between business customers, business analysts, testers and developers, however the business customers (product owners) are the primary owners of these tests. As the user stories pass their acceptance criteria, the business owners can be sure of the fact that the developers are progressing in the right direction about how the application was envisaged to work and so it's essential that these tests include both business logic tests as well as UI validation elements (if need be).

Acceptance test cards are ideally created during sprint planning or iteration planning meeting, before development begins so that the developers have a clear idea of what to develop. Sometimes (due to bad planning!) acceptance tests may span multiple stories (that are not implemented in the same sprint) and there are different ways to test them out during actual sprints. One popular technique is to mock external interfaces or data to mimic other stories which might not be played out during an iteration (as those stories may have been relatively lower business priority). A user story is not considered complete until the acceptance tests have passed.

Process

The acceptance test suite is run against the supplied input data or using an acceptance test script to direct the testers. Then the results obtained are compared with the expected results. If there is a correct match for every case, the test suite is said to pass. If not, the system may either be rejected or accepted on conditions previously agreed between the sponsor and the manufacturer.

The objective is to provide confidence that the delivered system meets the business requirements of both sponsors and users. The acceptance phase may also act as the final quality gateway, where any quality defects not previously detected may be uncovered.

A principal purpose of acceptance testing is that, once completed successfully, and provided certain additional (contractually agreed) acceptance criteria are met, the sponsors will then sign off on the system as satisfying the contract (previously agreed between sponsor and manufacturer), and deliver final payment.

User acceptance testing

User Acceptance Testing (UAT) is a process to obtain confirmation that a system meets mutually agreed-upon requirements. A Subject Matter Expert (SME), preferably the owner or client of the object under test, provides such confirmation after trial or review. In software development, UAT is one of the final stages of a project and often occurs before a client or customer accepts the new system.

Users of the system perform these tests, which developers derive from the client's contract or the user requirements specification.

Test-designers draw up formal tests and devise a range of severity levels. Ideally the designer of the user acceptance tests should not be the creator of the formal integration and system test cases for the same system, however in some situations this may not be avoided. The UAT acts as a final verification of the required business function and proper functioning of the system, emulating real-world usage conditions on behalf of the paying client or a specific large customer. If the software works as intended and without issues during normal use, one can reasonably extrapolate the same level of stability in production.

User tests, which are usually performed by clients or end-users, do not normally focus on identifying simple problems such as spelling errors and cosmetic problems, nor showstopper defects, such as software crashes; testers and developers previously identify and fix these issues during earlier unit testing, integration testing, and system testing phases.

The results of these tests give confidence to the clients as to how the system will perform in production. There may also be legal or contractual requirements for acceptance of the system.

Q-UAT - Quantified User Acceptance Testing

Quantified User Acceptance Testing (Q-UAT or, more simply, the "Quantified Approach") is a revised Business Acceptance Testing process which aims to provide a smarter and faster alternative to the traditional UAT phase. Depth-testing is carried out against business requirements only at specific planned points in the application or service under test. A reliance on better quality code-delivery from the development/build phase is assumed and a complete understanding of the appropriate business process is a pre-requisite. This methodology - if carried out correctly - results in a quick turnaround against plan, a decreased number of test scenarios which are more complex and wider in breadth than traditional UAT and ultimately the equivalent confidence-level attained via a shorter delivery-window, allowing products/changes to come to market quicker.

The Q-UAT approach depends on a "gated" three-dimensional model. The key concepts are:

1. Linear Testing (LT, the 1st dimension)
2. Recursive Testing (RT, the 2nd dimension)
3. Adaptive Testing (AT, the 3rd dimension).

The four "gates" which conjoin and support the 3-dimensional model act as quality safeguards and include contemporary testing concepts such as:

- Internal Consistency Checks (ICS)
- Major Systems/Services Checks (MSC)
- Realtime/Reactive Regression (RTR).

The Quantified Approach was shaped by the former "guerilla" method of acceptance testing which was itself a response to testing phases which proved too costly to be sustainable for many small/medium-scale projects.

Acceptance testing in Extreme Programming

Acceptance testing is a term used in agile software development methodologies, particularly Extreme Programming, referring to the functional testing of a user story by the software development team during the implementation phase.

The customer specifies scenarios to test when a user story has been correctly implemented. A story can have one or many acceptance tests, whatever it takes to ensure the functionality works. Acceptance tests are black box system tests. Each acceptance test represents some expected result from the system. Customers are responsible for verifying the correctness of the acceptance tests and reviewing test scores to decide which failed tests are of highest priority. Acceptance tests are also used as regression tests prior to a production release. A user story is not considered complete until it has passed its acceptance tests. This means that new acceptance tests must be created for each iteration or the development team will report zero progress.

Types of acceptance testing

Typical types of acceptance testing include the following

User acceptance testing
: This may include factory acceptance testing, i.e. the testing done by factory users before the factory is moved to its own site, after which site acceptance testing may be performed by the users at the site.

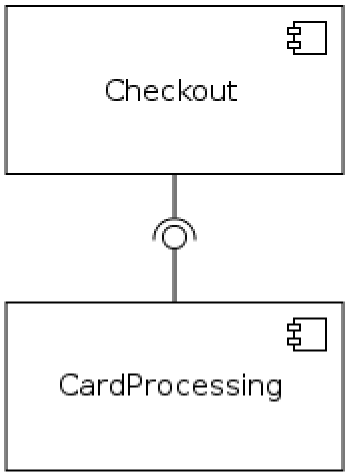
Operational Acceptance Testing (OAT)
: Also known as operational readiness testing, this refers to the checking done to a system to ensure that processes and procedures are in place to allow the system to be used and maintained. This may include checks done to back-up facilities, procedures for disaster recovery, training for end users, maintenance procedures, and security procedures.

Contract and regulation acceptance testing
: In contract acceptance testing, a system is tested against acceptance criteria as documented in a contract, before the system is accepted. In regulation acceptance testing, a system is tested to ensure it meets governmental, legal and safety standards.

Alpha and beta testing
: Alpha testing takes place at developers' sites, and involves testing of the operational system by internal staff, before it is released to external customers. Beta testing takes place at customers' sites, and involves testing by a group of customers who use the system at their own locations and provide feedback, before the system is released to other customers. The latter is often called “field testing”.

Chapter 8

Component-Based Software Engineering



A simple example of two components expressed in UML 2.0. The checkout component, responsible for facilitating the customer's order, *requires* the card processing component to charge the customer's credit/debit card (functionality which the latter *provides*).

Component-based software engineering (CBSE) (also known as **component-based development (CBD)**) is a branch of software engineering which emphasizes the separation of concerns in respect of the wide-ranging functionality available throughout a given software system. This practice aims to bring about an equally wide-ranging degree of benefits in both the short-term and the long-term for the software itself and for organizations that sponsor such software.

Software engineers regard components as part of the starting platform for service-orientation. Components play this role, for example, in Web Services, and more recently, in Service-Oriented Architecture (SOA) - whereby a component is converted into a *service* and subsequently inherits further characteristics beyond that of an ordinary component.

Components can produce events or consume events and can be used for event driven architecture (EDA).

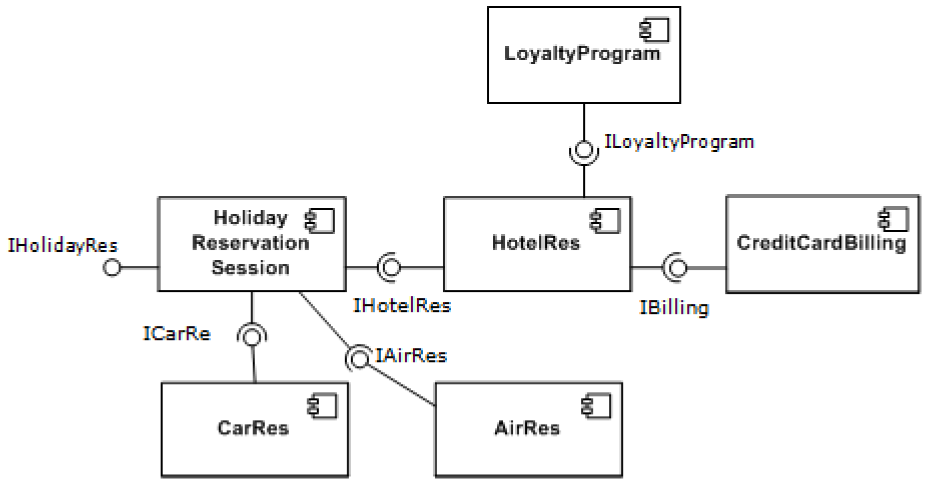
Definition and characteristics of components

An individual component is a software package, a web service, or a module that encapsulates a set of related functions (or data).

All system processes are placed into separate components so that all of the data and functions inside each component are semantically related (just as with the contents of classes). Because of this principle, it is often said that components are *modular* and *cohesive*.

With regard to system-wide co-ordination, components communicate with each other via *interfaces*. When a component offers services to the rest of the system, it adopts a *provided* interface which specifies the services that other components can utilize, and how they can do so. This interface can be seen as a signature of the component - the client does not need to know about the inner workings of the component (implementation) in order to make use of it. This principle results in components referred to as *encapsulated*.

However when a component needs to use another component in order to function, it adopts a *used* interface which specifies the services that it needs. In the UML illustrations here, *used interfaces* are represented by an open socket symbol attached to the outer edge of the component.



A simple example of several software components - pictured within a hypothetical holiday-reservation system represented in UML 2.0.

Another important attribute of components is that they are *substitutable*, so that a component can replace another (at design time or run-time), if the successor component meets the requirements of the initial component (expressed via the interfaces). Consequently, components can be replaced with either an updated version or an alternative without breaking the system in which the component operates.

As a general rule of thumb for engineers substituting components, component B can immediately replace component A if component B provides at least what component A provided, and uses no more than what component A used.

Software components often take the form of objects (not classes) or collections of objects (from object-oriented programming), in some binary or textual form, adhering to some interface description language (IDL) so that the component may exist autonomously from other components in a computer.

When a component is to be accessed or shared across execution contexts or network links, techniques such as serialization or marshalling are often employed to deliver the component to its destination.

Reusability is an important characteristic of a high-quality software component. Programmers should design and implement software components in such a way that many different programs can reuse them. Furthermore, component-based usability testing should be considered when software components directly interact with users.

It takes significant effort and awareness to write a software component that is effectively reusable. The component needs to be:

- fully documented
- thoroughly tested
    - robust - with comprehensive input-validity checking
    - able to pass back appropriate error messages or return codes
- designed with an awareness that it *will* be put to unforeseen uses

In the 1960s, programmers built scientific subroutine libraries that were reusable in a broad array of engineering and scientific applications. Though these subroutine libraries reused well-defined algorithms in an effective manner, they had a limited domain of application. Commercial sites routinely created application programs from reusable modules written in Assembler, COBOL, PL/1 and other second- and third-generation languages using both System and user application libraries.

As of 2010, modern reusable components encapsulate both data structures and the algorithms that are applied to the data structures. It builds on prior theories of software objects, software architectures, software frameworks and software design patterns, and the extensive theory of object-oriented programming and the object oriented design of all these. It claims that software components, like the idea of hardware components, used for example in telecommunications, can ultimately be made interchangeable and reliable. On the other hand, it is argued that it is a mistake to focus on independent components rather than the framework (without which they would not exist).

History

The idea that software should be componentized - built from prefabricated *components* - first became prominent with Douglas McIlroy's address at the NATO conference on software engineering in Garmisch, Germany, 1968, titled *Mass Produced Software Components*. The conference set out to counter the so-called software crisis. McIlroy's subsequent inclusion of pipes and filters into the Unix operating system was the first implementation of an infrastructure for this idea.

Brad Cox of Stepstone largely defined the modern concept of a software component. He called them *Software ICs* and set out to create an infrastructure and market for these components by inventing the Objective-C programming language. (He summarizes this view in his book *Object-Oriented Programming - An Evolutionary Approach* 1986.)

IBM led the path with their System Object Model (SOM) in the early 1990s. Some claim that Microsoft paved the way for actual deployment of component software with OLE and COM. As of 2010 many successful software component models exist.

Differences from object-oriented programming

Proponents of object-oriented programming (OOP) maintain that software should be written according to a mental model of the actual or imagined objects it represents. OOP and the related disciplines of object-oriented design and object-oriented analysis focus on modeling real-world interactions and attempting to create "verbs" and "nouns" which can be used in more human-readable ways, ideally by end users as well as by programmers coding for those end users.

Component-based software engineering, by contrast, makes no such assumptions, and instead states that developers should construct software by gluing together prefabricated components - much like in the fields of electronics or mechanics. Some peers will even talk of modularizing systems as software components as a new programming paradigm.

Some argue that earlier computer scientists made this distinction, with Donald Knuth's theory of "literate programming" optimistically assuming there was convergence between intuitive and formal models, and Edsger Dijkstra's theory in *The Cruelty of Really Teaching Computer Science*, which stated that programming was simply, and only, a branch of mathematics.

In both forms, this notion has led to many academic debates about the pros and cons of the two approaches and possible strategies for uniting the two. Some consider the different strategies not as competitors, but as descriptions of the same problem from different points of view.

Architecture

A computer running several software components is often called an application server. Using this combination of application servers and software components is usually called distributed computing. The usual real-world application of this is in e.g. financial applications or business software.

Technologies

- Pipes and Filters
    - Unix operating system
- Component-oriented programming
    - SOFA component system from ObjectWeb
    - Fractal component model from ObjectWeb
    - rCOS method of component-based model driven design from UNU-IIST
    - Visual Basic Extensions, OCX/ActiveX/COM and DCOM from Microsoft
    - XPCOM from Mozilla Foundation
    - VCL and CLX from Borland and similar free LCL library.
    - Enterprise JavaBeans from Sun Microsystems (now Oracle)
    - UNO from the OpenOffice.org office suite
    - Eiffel programming language
    - Oberon, Component Pascal, and BlackBox Component Builder
    - Bundles as defined by the OSGi Service Platform
    - The `System.ComponentModel` namespace in Microsoft .NET
    - Flow-based programming
    - MidCOM component framework for Midgard and PHP
    - Common Component Architecture (CCA) - Common Component Architecture Forum , Scientific/HPC Component Software
        - TASCS - SciDAC Center for Technology for Advanced Scientific Component Software
- Component-based software frameworks for specific domains
    - Earth System Modeling Framework (ESMF)
- Compound document technologies
    - Active Documents in Oberon System and BlackBox Component Builder
    - Bonobo (component model), a part of GNOME
    - KPart, the KDE Compound document technology
    - Object linking and embedding (OLE)
    - OpenDoc
    - Fresco
- Business object technologies
    - Newi
- Distributed computing software components
    - 9P distributed protocol developed for Plan 9, and used by Inferno and other systems.
    - CORBA and the CORBA Component Model from the Object Management Group

    - D-BUS from the freedesktop.org organization
    - DCOM and later versions of COM (and COM+) from Microsoft
    - DCOP from KDE
    - DSOM and SOM from IBM (now scrapped)
    - ICE from ZeroC
    - Java EE from Sun
    - .NET Remoting from Microsoft
    - Web Services
        - REST
    - Universal Network Objects (UNO) from OpenOffice.org
    - Zope from Zope Corporation
- Interface description languages
    - XML-RPC, the predecessor of SOAP
    - SOAP IDL from W3C
    - WDDX
    - Part of both COM and CORBA
    - Open Service Interface Definitions
    - Platform-Independent Component Modeling Language
    - SIDL - Scientific Interface Definition Language
        - Part of the Babel Scientific Programming Language Interoperability System
        - (SIDL and Babel are core technologies of the CCA and the SciDAC TASCS Center - see above.)
- Generic programming emphasizes separation of algorithms from data representation
- Inversion of Control (IoC) and Plain Old C++/Java Object (POCO/POJO) component frameworks

Chapter 9

Flow-based Programming

In computer science, **flow-based programming** (**FBP**) is a programming paradigm that defines applications as networks of "black box" processes, which exchange data across predefined connections by message passing, where the connections are specified *externally* to the processes. These black box processes can be reconnected endlessly to form different applications without having to be changed internally. FBP is thus naturally component-oriented.

FBP is a particular form of dataflow programming based on bounded buffers, information packets with defined lifetimes, named ports, and separate definition of connections.

Introduction

The FBP development approach views an application not as a single, sequential, process, which starts at a point in time, and then does one thing at a time until it is finished, but as a network of asynchronous processes communicating by means of streams of structured data chunks, called "information packets" (IPs). In this view, the focus is on the application data and the transformations applied to it to produce the desired outputs. The network is defined externally to the processes, as a list of connections which is interpreted by a piece of software, usually called the "scheduler".

The processes communicate by means of fixed-capacity connections. A connection is attached to a process by means of a port, which has a name agreed upon between the process code and the network definition. More than one process can execute the same piece of code. At any point in time, a given IP can only be "owned" by a single process, or be in transit between two processes. Ports may either be simple, or array-type, as used e.g. for the input port of the Collate component described below. It is the combination of ports with asynchronous processes that allows many long-running primitive functions of data processing, such as Sort, Merge, Summarize, etc., to be supported in the form of software black boxes.

Because FBP processes can continue executing as long they have data to work on and somewhere to put their output, FBP applications generally run in less elapsed time than conventional programs, and make optimal use of all the processors on a machine, with no special programming required to achieve this.

The network definition is usually diagrammatic, and is converted into a connection list in some lower-level language or notation. FBP is thus a visual programming language at this level. More complex network definitions have a hierarchical structure, being built up from subnets with "sticky" connections.

FBP has much in common with the Linda language in that it is, in Gelernter and Carriero's terminology, a "coordination language": it is essentially language-independent. Indeed, given a scheduler written in a sufficiently low-level language, components written in different languages can be linked together in a single network. FBP thus lends itself to the concept of domain-specific languages or "mini-languages".

FBP exhibits "data coupling", described in coupling as the loosest type of coupling between components. The concept of loose coupling is in turn related to that of Service-oriented architectures, and FBP fits a number of the criteria for such an architecture, albeit at a more fine-grained level than most examples of this architecture.

FBP promotes high-level, functional style of specifications that simplify reasoning about system behavior. An example of this is the distributed data flow model for constructively specifying and analyzing the semantics of distributed multi-party protocols.

History

FBP was invented by J. Paul Morrison in the early 1970s, and an early implementation of this technology has been in continuous production use at a major Canadian bank since that time.

FBP at its inception was strongly influenced by some IBM simulation languages of the period, in particular GPSS, but its roots go all the way back to Conway's seminal paper on what he called coroutines.

FBP has undergone a number of name changes over the years: the original implementation was called AMPS (Advanced Modular Processing System), which (as of 2008) has been in continuous production use since the early 1970s at a major Canadian bank. A number of the basic concepts were put into the public domain by IBM, by means of a Technical Disclosure Bulletin in 1971, using a very general title. An article describing its concepts and experience using it was published in 1978 in the IBM Research IBM Systems Journal under the name DSLM. A second implementation was done as a joint project of IBM Canada and IBM Japan, under the name "Data Flow Development Manager" (DFDM), and was briefly marketed in Japan in the late '80s under the name "Data Flow Programming Manager".

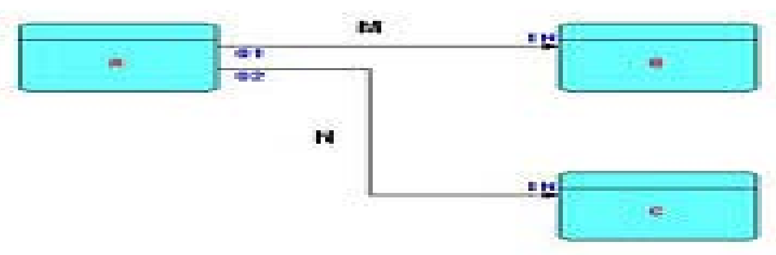
Generally the concepts were referred to within IBM as "Data Flow", but this term was felt to be too general, and eventually the name Flow-Based Programming was adopted, and a book with that title was published in 1994. The 2nd edition is now available, published by CreateSpace, a DBA of On-Demand Publishing LLC, part of the Amazon.com group of companies.

The late IBM architect, Wayne Stevens, wrote several articles describing and supporting the FBP concept, and included material about it in several of his books.

As of 2009 several companies were marketing tools based on FBP concepts, among them: Trelliswerk LLC, Proto Software, Inc., InforSense, Accelrys, and open-source Kettle and Knime. IBM also sells a tool for general data transformation called DataStage which combines FBP with parallel processing.

Concepts

The following diagram shows the major entities of an FBP diagram (apart from the Information Packets). Such a diagram can be converted directly into a list of connections, which can then be executed by an appropriate engine (software or hardware).



Simple FBP diagram

A, B and C are processes executing code components. O1, O2, and the two INs are ports connecting the connections M and N to their respective processes. It is permitted for processes B and C to be executing the same code, so each process must have its own set of working storage, control blocks, etc. Whether or not they do share code, B and C are free to use the same port names, as port names only have meaning within the components referencing them (and at the network level, of course).

M and N are what are often referred to as "bounded buffers", and have a fixed capacity in terms of the number of IPs that they can hold at any point in time.

The concept of *ports* is what allows the same component to be used at more than one place in the network. In combination with a parametrization capability, called Initial Information Packets (IIPs), ports provide FBP with a component reuse capability, making FBP a component-based architecture. FBP thus exhibits what Nate Edwards of IBM Research has termed configurable modularity.

Information Packets or IPs are allocated in what might be called "IP space" (just as Linda's tuples are allocated in "tuple space"), and have a well-defined lifetime until they are disposed of and their space is reclaimed - in FBP this must be an explicit action on the part of an owning process. IPs traveling across a given connection (actually it is their "handles" that travel) constitute a "stream", which is generated and consumed asynchronously - this concept thus has similarities to the lazy cons concept described in the 1976 article by Friedman and Wise.

IPs are usually structured chunks of data - some IPs, however, may not contain any real data, but are used simply as signals. An example of this is "bracket IPs", which can be used to group data IPs into sequential patterns within a stream, called "substreams". Substreams may in turn be nested. IPs may also be chained together to form "IP trees", which travel through the network as single objects.

The system of connections and processes described above can be "ramified" to any size. During the development of an application, monitoring processes may be added between pairs of processes, processes may be "exploded" to subnets, or simulations of processes may be replaced by the real process logic. FBP therefore lends itself to rapid prototyping.

This is really an assembly line image of data processing: the IPs travelling through a network of processes may be thought of as widgets travelling from station to station in an assembly line. "Machines" may easily be reconnected, taken off line for repair, replaced, and so on. Oddly enough, this image is very similar to that of unit record equipment that was used to process data before the days of computers, except that decks of cards had to be hand-carried from one machine to another.

Implementations of FBP may be non-preemptive or preemptive - the earlier implementations tended to be non-preemptive (mainframe and C language), whereas the latest Java implementation (see below) uses Java Thread class and is preemptive.

Implementations

After Paul Morrison retired from IBM, these concepts were implemented first in C++, using green threads (this version is currently undergoing conversion to fibers), then in Java, starting from a base developed by John Cowan - this implementation is available as Open Source on SourceForge. A C# implementation is also available at the same site. Both of these implementations use threads, so they make optimum use of all the processors on the machine running the application.

A diagramming tool, called "DrawFBP", is also available at that site - it can also be run via JWS.

Examples

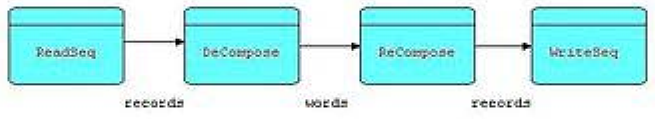
"Telegram Problem"

FBP components often form complementary pairs. This example uses two such pairs. The problem described seems very simple as described in words, but in fact is surprisingly hard to do using conventional procedural logic. The task, called the "Telegram Problem", originally described by Peter Naur, is to write a program which accepts lines of text and generates output lines of a different length, without splitting any of the words in the text (we assume no word is longer than the size of the output lines).

In conventional logic, the programmer rapidly discovers that neither the input nor the output structures can be used to drive the call hierarchy of control flow. In FBP, on the other hand, the problem description itself suggests a solution:

- "words" are mentioned explicitly in the description of the problem, so it is reasonable for the designer to treat words as information packets (IPs)
- in FBP there is no single call hierarchy, so the programmer is not tempted to force a subpattern of the solution to be the top level.

Here is the most natural solution in FBP (there is no single "correct" solution in FBP, but this seems like a natural fit):

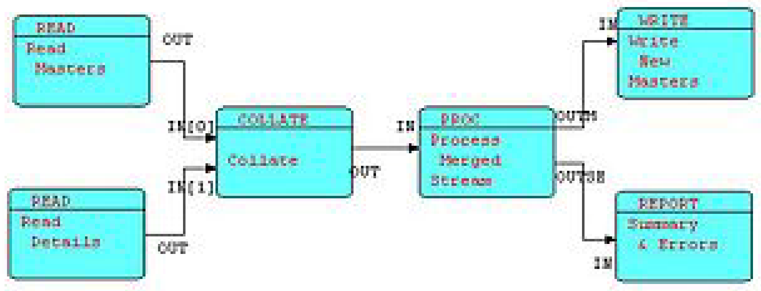


"Telegram problem"

As mentioned above, Initial Information Packets (IIPs) can be used to specify parametric information such as the desired output record length (required by the rightmost two components), or file names. IIPs are data chunks associated with a port in the network definition which become "normal" IPs when a "receive" is issued for the relevant port.

Batch update

This type of program involves passing a file of "details" (changes, adds and deletes) against a "master file", and producing (at least) an updated master file, and one or more reports. Update programs are generally quite hard to code using synchronous, procedural code, as two (sometimes more) input streams have to be kept synchronized, even though there may be masters without corresponding details, or vice versa.



Update

In FBP, a reusable component (Collate), based on the unit record idea of a Collator, makes writing this type of application much easier as Collate merges the two streams and inserts bracket IPs to indicate grouping levels, significantly simplifying the downstream logic. Suppose that one stream ("masters" in this case) consists of IPs with key values of 1, 2 and 3, and the second stream IPs ("details") have key values of 11, 12, 21, 31, 32, 33 and 41, where the first digit corresponds to the master key values. Using bracket characters to represent "bracket" IPs, the collated output stream will be as follows:

```
( m1 d11 d12 ) ( m2 d21 ) ( m3 d31 d32 d33 ) (d41)
```

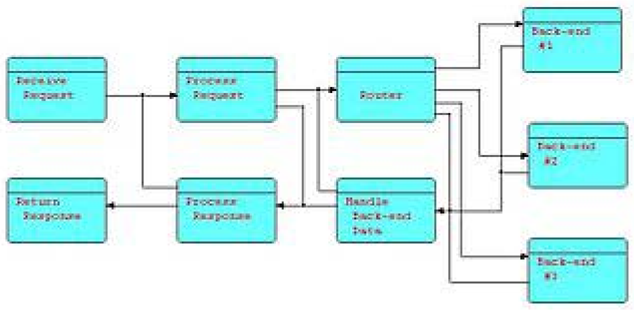
As there was no master with a value of 4, the last group consists of a single detail (plus brackets).

The structure of the above stream can be described succinctly using a BNF-like notation such as

```
{ ( [m] d* ) }*
```

Collate is a reusable black box which only needs to know where the control fields are in its incoming IPs (even this is not strictly necessary as transformer processes can be inserted upstream to place the control fields in standard locations), and can in fact be generalized to any number of input streams, and any depth of bracket nesting. Collate uses an array-type port for input, allowing a variable number of input streams.

Simple interactive network



Schematic of general interactive application

In this general schematic, requests (transactions) coming from users enter the diagram at the upper left, and responses are returned at the lower left. The "back ends" (on the right side) communicate with systems at other sites, e.g. using CORBA, MQSeries, etc. The cross-connections represent requests that do not need to go to the back ends, or requests that have to cycle through the network more than once before being returned to the user.

As different requests may use different back-ends, and may require differing amounts of time for the back-ends (if used) to process them, provision must be made to relate returned data to the appropriate requesting transactions, e.g. hash tables or caches.

The above diagram is schematic in the sense that the final application may contain many more processes: processes may be inserted between other processes to manage caches, display connection traffic, monitor throughput, etc. Also the blocks in the diagram may represent "subnets" - small networks with one or more open connections.

Comparison with other paradigms and methodologies

Jackson Structured Programming (JSP)

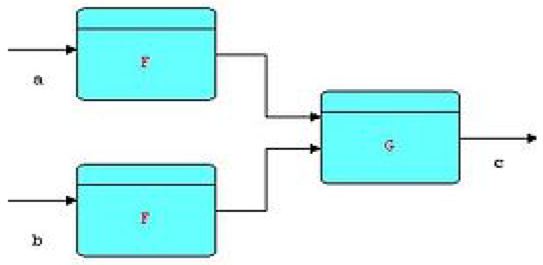
This methodology assumes that a program must be structured as a single procedural hierarchy of subroutines. Its starting point is to describe the application as a set of "main lines", based on the input and output data structures. One of these "main lines" is then chosen to drive the whole program, and the others are required to be "inverted" to turn them into subroutines (hence the name "Jackson inversion"). This sometimes results in what is called a "clash", requiring the program to be split into multiple programs or coroutines. When using FBP, this inversion process is not required, as every FBP component can be considered a separate "main line".

FBP and JSP share the concept of treating a program (or some components) as a parser of an input stream. The FBP book contains a discussion of how the concept of push-down automata may be used to design components (Chapter 23). It describes how a stack of controlling IPs may be used to control nested substreams in an FBP data stream.

Applicative programming

W.B. Ackerman defines an applicative language as one which does all of its processing by means of operators applied to values. The earliest known applicative language was LISP.

An FBP component can be regarded as a function transforming its input stream(s) into its output stream(s). These functions are then combined to make more complex transformations, as shown here:



Two functions feeding one

If we label streams, as shown, with lower case letters, then the above diagram can be represented succinctly as follows:

```
c = G(F(a),F(b));
```

Just as in functional notation F can be used twice because it only works with values, and therefore has no side effects, in FBP two instances of a given component may be running concurrently with each other, and therefore FBP components must not have side-effects either. Functional notation could clearly be used to represent at least a part of an FBP network.

The question then arises whether FBP components can themselves be expressed using functional notation. W.H. Burge showed how stream expressions can be developed using a recursive, applicative style of programming, but this work was in terms of (streams of) atomic values. In FBP, it is necessary to be able to describe and process structured data chunks (FBP IPs). In the FBP book, a notation is added for accessing the fields of an IP, and an operator, called the "mini-constructor" (μ), based on a similar function in the Vienna Definition Language, for creating an IP from a set of (perhaps modified) field values and identifiers.

Furthermore, most applicative systems assume that all the data is available in memory at the same time, whereas FBP applications need to be able to process long-running streams of data while still using finite resources. Friedman and Wise suggested a way to do this by adding the concept of "lazy cons" to Burge's work. This removed the requirement that both of the arguments of "cons" be available at the same instant of time. "Lazy cons" does not actually build a stream until both of its arguments are realized - before that it simply records a "promise" to do this. This allows a stream to be dynamically realized from the front, but with an unrealized back end. The end of the stream stays unrealized until the very end of the process, while the beginning is an ever-lengthening sequence of items.

In the FBP book (Chapter 24), these ideas are combined to allow the expression of some quite complex component logic using applicative notation.

Linda

Many of the concepts in FBP seem to have been discovered independently in different systems over the years. Linda, mentioned above, is one such. Chapter 26 of the FBP book goes into some detail about similarities and differences, but probably the major difference is that, in Linda, data is accessed associatively, whereas in FBP, IPs arriving at a particular input port are retrieved sequentially. FBP's IPs are very similar to Linda's tuples. The difference between the two techniques is illustrated by the Linda "school of piranhas" load balancing technique - in FBP, this requires an extra "load balancer" component which routes requests to the component in a list which has the smallest number of IPs waiting to be processed. Clearly FBP and Linda are closely related, and one could easily be used to simulate the other.

Object-oriented programming

An object in OOP can be described as a semi-autonomous unit comprising both information and behaviour. Objects communicate by means of "method calls", which are essentially subroutine calls, done indirectly via the class to which the receiving object belongs. The object's internal data can only be accessed by means of method calls, so this is a form of information hiding or "encapsulation". Encapsulation, however, predates OOP - David Parnas wrote one of the seminal articles on it in the early 70s - and is a basic concept in computing. Encapsulation is the very essence of an FBP component, which may be thought of as a black box, performing some conversion of its input data into its output data. In FBP, part of the specification of a component is the data formats and stream structures that it can accept, and those it will generate. This constitutes a form of design by contract. In addition, the data in an IP can only be accessed directly by the currently owning process. Encapsulation can also be implemented at the network level, by having outer processes protect inner ones.

A paper by C. Ellis and S. Gibbs distinguishes between active objects and passive objects. Passive objects comprise information and behaviour, as stated above, but they cannot determine the *timing* of this behaviour. Active objects on the other hand can do this. In their article Ellis and Gibbs state that active objects have much more potential for the development of maintainable systems than do passive objects. An FBP application can be viewed as a combination of these two types of object, where FBP processes would correspond to active objects, while IPs would correspond to passive objects.

Chapter 25 of the FBP book goes into more detail on the relationship between FBP and OOP.

Chapter 10

Pipeline (Software)

In software engineering, a **pipeline** consists of a chain of processing elements (processes, threads, coroutines, *etc.*.), arranged so that the output of each element is the input of the next. Usually some amount of buffering is provided between consecutive elements. The information that flows in these pipelines is often a stream of records, bytes or bits.

The concept is also called the **pipes and filters design pattern**. It was named by analogy to a physical pipeline.

Multiprocessed pipelines

Pipelines are often implemented in a multitasking OS, by launching all elements at the same time as processes, and automatically servicing the data read requests by each process with the data written by the upstream process. In this way, the CPU will be naturally switched among the processes by the scheduler so as to minimize its idle time. In other common models, elements are implemented as lightweight threads or as coroutines to reduce the OS overhead often involved with processes. Depending upon the OS, threads may be scheduled directly by the OS or by a thread manager. Coroutines are always scheduled by a coroutine manager of some form.

Usually, read and write requests are blocking operations, which means that the execution of the source process, upon writing, is suspended until all data could be written to the destination process, and, likewise, the execution of the destination process, upon reading, is suspended until at least some of the requested data could be obtained from the source process. Obviously, this cannot lead to a deadlock, where both processes would wait indefinitely for each other to respond, since at least one of the two processes will soon thereafter have its request serviced by the operating system, and continue to run.

For performance, most operating systems implementing pipes use pipe buffers, which allow the source process to provide more data than the destination process is currently able or willing to receive. Under most Unices and Unix-like operating systems, a special command is also available which implements a pipe buffer of potentially much larger and configurable size, typically called "buffer". This command can be useful if the destination process is significantly slower than the source process, but it is anyway desired that the source process can complete its task as soon as possible. E.g., if the source process consists of a command which reads an audio track from a CD and the destination process consists of a command which compresses the waveform audio data to a format like MP3. In this case, buffering the entire track in a pipe buffer would allow the CD drive to spin down more quickly, and enable the user to remove the CD from the drive before the encoding process has finished.

Such a buffer command can be implemented using available operating system primitives for reading and writing data. Wasteful busy waiting can be avoided by using facilities such as poll or select or multithreading.

VM/CMS and MVS

CMS Pipelines is a port of the pipeline idea to VM/CMS and MVS systems. It supports much more complex pipeline structures than Unix shells, with steps taking multiple input streams and producing multiple output streams. (Such functionality is supported by the Unix kernel, but few programs use it as it makes for complicated syntax and blocking modes, although some shells do support it via arbitrary file descriptor assignment). Due to the different nature of IBM mainframe operating systems, it implements many steps inside CMS Pipelines which in Unix are separate external programs, but can also call separate external programs for their functionality. Also, due to the record-oriented nature of files on IBM mainframes, pipelines operate in a record-oriented, rather than stream-oriented manner.

Pseudo-pipelines

On single-tasking operating systems, the processes of a pipeline have to be executed one by one in sequential order; thus the output of each process must be saved to a temporary file, which is then read by the next process. Since there is no parallelism or CPU switching, this version is called a "pseudo-pipeline".

For example, the command line interpreter of MS-DOS ('COMMAND.COM') provides pseudo-pipelines with a syntax superficially similar to that of Unix pipelines. The command "dir | sort | more" would have been executed like this (albeit with more complicated temporary file names):

1. Create temporary file 1.tmp
2. Run command "dir", redirecting its output to 1.tmp
3. Create temporary file 2.tmp
4. Run command "sort", redirecting its input to 1.tmp and its output to 2.tmp
5. Run command "more", redirecting its input to 2.tmp, and presenting its output to the user
6. Delete 1.tmp and 2.tmp, which are no longer needed
7. Return to the command prompt

All temporary files are stored in the directory pointed to by %TEMP%, or the current directory if %TEMP% isn't set.

Thus, pseudo-pipes acted like true pipes with a pipe buffer of unlimited size (disk space limitations notwithstanding), with the significant restriction that a receiving process could not read *any* data from the pipe buffer until the sending process finished completely. Besides causing disk traffic, if one doesn't install a harddisk cache such as SMARTDRV, that would have been unnecessary under multi-tasking operating systems, this implementation also made pipes unsuitable for applications requiring real-time response, like, for example, interactive purposes (where the user enters commands that the first process in the pipeline receives via stdin, and the last process in the pipeline presents its output to the user via stdout).

Also, commands that produce a potentially infinite amount of output, such as the yes command, cannot be used in a pseudo-pipeline, since they would run until the temporary disk space is exhausted, so the following processes in the pipeline could not even start to run.

Object pipelines

Beside byte stream-based pipelines, there are also object pipelines. In an object pipeline, the processes output objects instead of texts; therefore removing the string parsing tasks that are common in UNIX shell scripts. Windows PowerShell uses this scheme and transfers .NET objects. Channels, found in the Limbo programming language, and the IPython ipipe extension are other examples of this metaphor.

Pipelines in GUIs

Graphical environments such as RISC OS and ROX Desktop also make use of pipelines. Rather than providing a save dialog box containing a file manager to let the user specify where a program should write data, RISC OS and ROX provide a save dialog box containing an icon (and a field to specify the name). The destination is specified by dragging and dropping the icon. The user can drop the icon anywhere an already-saved file could be dropped, including onto icons of other programs. If the icon is dropped onto a program's icon, it's loaded and the contents that would otherwise have been saved are passed in on the new program's standard input stream.

For instance, a user browsing the world-wide web might come across a .gz compressed image which they want to edit and re-upload. Using GUI pipelines, they could drag the link to their de-archiving program, drag the icon representing the extracted contents to their image editor, edit it, open the save as dialog, and drag its icon to their uploading software.

Conceptually, this method could be used with a conventional save dialog box, but this would require the user's programs to have an obvious and easily-accessible location in the filesystem that can be navigated to. In practice, this is often not the case, so GUI pipelines are rare.

Other considerations

The name 'pipeline' comes from a rough analogy with physical plumbing in that a pipeline usually allows information to flow in only one direction, like water often flows in a pipe.

Pipes and filters can be viewed as a form of functional programming, using byte streams as data objects; more specifically, they can be seen as a particular form of monad for I/O.

The concept of pipeline is also central to the Cocoon web development framework or to any XProc (the W3C Standards) implementations, where it allows a source stream to be modified before eventual display.

This pattern encourages the use of text streams as the input and output of programs. This reliance on text has to be accounted when creating graphic shells to text programs.

History

Process pipelines were invented by Douglas McIlroy, one of the designers of the first Unix shells, and greatly contributed to the popularity of that operating system. It can be considered the first non-trivial instance of software componentry.

The idea was eventually ported to other operating systems, such as DOS, OS/2, Windows NT, BeOS, AmigaOS, MorphOS and Mac OS X (the latter being a UNIX OS).

Chapter 11

DirectSound

DirectSound is a software component of the DirectX library, supplied by Microsoft, that resides on a computer with the Windows operating system. It provides a direct interface between applications and the sound card drivers on Windows XP and earlier operating systems, enabling applications to produce sounds and music. Besides providing the essential service of passing audio data to the sound card, it provides many needed capabilities such as recording and mixing sound; adding effects to sound e.g. reverb, echo, flange; using hardware controlled buffers for extra speed; positioning sounds in 3D space (3D audio spatialization), capturing sounds from a microphone or other input and controlling capture effects during audio capture.

DirectSound also allows several applications to conveniently share access to the sound card at the same time. Its ability to play sound in 3D added a new dimension to games. It also provides the ability for games to modify a musical script in response to game events in real time, e.g. the beat of the music could quicken as the action heats up.

After many years of development, today DirectSound is a very mature API, and supplies many other useful capabilities, such as the ability to play multichannel sounds at high resolution. While DirectSound was designed to be used by games, a number of professional audio applications now take advantage of its diverse capabilities.

DirectSound3D

DirectSound3D (DS3D) is an addition to Microsoft's DirectX system which is intended to standardize 3D audio under Microsoft Windows, introduced with DirectX 3 in 1996.

DirectSound3D allows software developers to write to a single standardized audio API instead of writing code for each audio card manufacturer.

In DirectX 5, DirectSound3D has the capability of having sound cards that use third party 3D audio algorithms accelerate DirectSound3D properly, through Microsoft-approved methods. This eliminates the need for separate 3D audio libraries.

Starting with DirectX 8 onwards, DirectSound and DirectSound3D (DS3D) are together referred to as **DirectX Audio**.

Windows Vista

Windows Vista features a completely re-written audio stack based on the *Universal Audio Architecture*. Because of the architectural changes in the redesigned audio stack, a direct path from DirectSound to the audio drivers does not exist. DirectSound and other APIs such as MME are emulated as WASAPI Session instances. DirectSound runs in emulation mode on the Microsoft software mixer. The emulator does not have hardware abstraction, so there is no hardware DirectSound acceleration, meaning hardware and software relying on DirectSound acceleration may have degraded performance. It's likely a supposed performance hit might not be noticeable, depending on the application and actual system hardware. In the case of hardware 3D audio effects played using DirectSound3D, they will not be playable.

Third-party APIs such as ASIO and OpenAL are not affected by these architectural changes in Windows Vista. A solution for applications that wish to take advantage of hardware accelerated high-quality 3D positional audio is to use OpenAL. However, this only works if the manufacturer provides an OpenAL driver for their hardware.

As of 2007, a solution to re-enable hardware acceleration of DirectSound3D and Audio Effects, such as EAX, called *Creative ALchemy* was launched. Creative ALchemy intercepts calls to DirectSound3D and translates them into OpenAL calls to be processed by supported hardware such as Sound Blaster X-Fi and Sound Blaster Audigy. For software-based Creative audio solutions, ALchemy utilizes its built-in 3D audio engine without using OpenAL at all.

Realtek, a manufacturer of integrated HD audio codecs, has a product similar to ALchemy called 3D SoundBack. C-Media, a manufacturer of PC sound card chipsets, also has a solution called Xear3D EX, although it works instead by intercepting DirectSound3D calls transparently in the background without any user intervention.

XAudio 2

Because of Xbox 360 and Microsoft Windows integration, Microsoft is actively pushing developers to migrate new applications to equivalent Xbox audio APIs such as XAudio and the Cross-platform Audio Creation Tool (XACT). XAudio is an Xbox-only API designed for digital signal processing, however, XAudio 2 is a cross-platform (Windows and Xbox) common low-level audio API, intended as the replacement for DirectSound. The RTM version of the XAudio 2 library is included in the March 2008 DirectX SDK. The target platforms include Windows XP, Windows Vista and the Xbox 360. XAudio 2 provides low-level mixing and signal processing whereas high-level audio authoring and playback are available using XACT and 3D functions via the X3DAudio library. The XACT engine is a high-level audio programming library that operates through XAudio on the Xbox, as a DirectSound passthrough on Windows XP, and directly on the low-level audio renderer in the new audio stack on Windows Vista. X3DAudio is an abstracted math-driven spatialization helper library that can be replaced by custom 3D behaviors.

Xaudio 2 has special emphasis on signal processing for high-level audio APIs such as XACT. Some of its features are:

- Separation of sound data from “voice”
- Submixing (arbitrary levels and routings)
- Multi-rate processing
- Per-voice filtering (built-in, in addition to programmable DSP effects)
- Programmable voices
- Effects processing, Sample rate conversion (SRC)
- Software DSP
- Enhanced surround sound (multichannel) and explicit multichannel panning/mapping dynamically to any speaker
- Native compressed data support
    - XMA on Xbox 360
    - ADPCM and xWMA (Windows Media Audio bitstream format in a lightweight wrapper) on Windows
    - Extensible
- 3D audio handled as a separate replaceable library: XAudio 2 takes multichannel speaker volumes and X3DAudio library transforms source/listener coordinates into speaker volumes and other synthesis parameters

Windows CE

Although DirectSound support was available in Windows CE versions up to 4.2, it was removed starting 5.0 . Windows CE 6.0 also does not support DirectSound, instead favoring that applications be rewritten to use the Waveform Audio API.

Chapter 12

Common Object Request Broker Architecture

The **Common Object Request Broker Architecture** (CORBA) is a standard defined by the Object Management Group (OMG) that enables software components written in multiple computer languages and running on multiple computers to work together (i.e., it supports multiple platforms).

Overview

CORBA is useful because it enables separate pieces of software written in different languages and running on different computers to work with each other like a single application or set of services. More specifically, CORBA is a mechanism in software for normalizing the method-call semantics between application objects residing either in the same address space (application) or remote address space (same host, or remote host on a network). Version 1.0 was released in October 1991. CORBA uses an interface definition language (IDL) to specify the interfaces which objects present to the outer world. CORBA then specifies a *mapping* from IDL to a specific implementation language like C++ or Java. Standard mappings exist for Ada, C, C++, Lisp, Ruby, Smalltalk, Java, COBOL, PL/I and Python. There are also non-standard mappings for Perl, Visual Basic, Erlang, and Tcl implemented by object request brokers (ORBs) written for those languages.

The CORBA specification dictates there shall be an ORB through which an application would interact with other objects. In practice, the application simply initializes the ORB, and accesses an internal *Object Adapter*, which maintains things like reference counting, object (and reference) instantiation policies, and object lifetime policies. The Object Adapter is used to register instances of the *generated code classes*. Generated code classes are the result of compiling the user IDL code, which translates the high-level interface definition into an OS- and language-specific class base for use by the user application. This step is necessary in order to enforce CORBA semantics and provide a clean user process for interfacing with the CORBA infrastructure.

Some IDL language mappings are more difficult to use than others. For example, due to the nature of Java, the IDL-Java mapping is rather straightforward and makes usage of CORBA very simple in a Java application. This is also true of the IDL to Python mapping. The C++ mapping is notoriously difficult; the mapping requires the programmer to learn complex and confusing datatypes that predate the C++ STL. Since the C language is not object-oriented, the IDL to C mapping requires a C programmer to manually emulate object oriented features.

A language mapping requires the developer to create IDL code that represents the interfaces to his objects. Typically, a CORBA implementation comes with a tool called an IDL compiler which converts the user's IDL code into some language-specific generated code. A traditional compiler then compiles the generated code to create the linkable-object files for the application. This diagram illustrates how the generated code is used within the CORBA infrastructure:

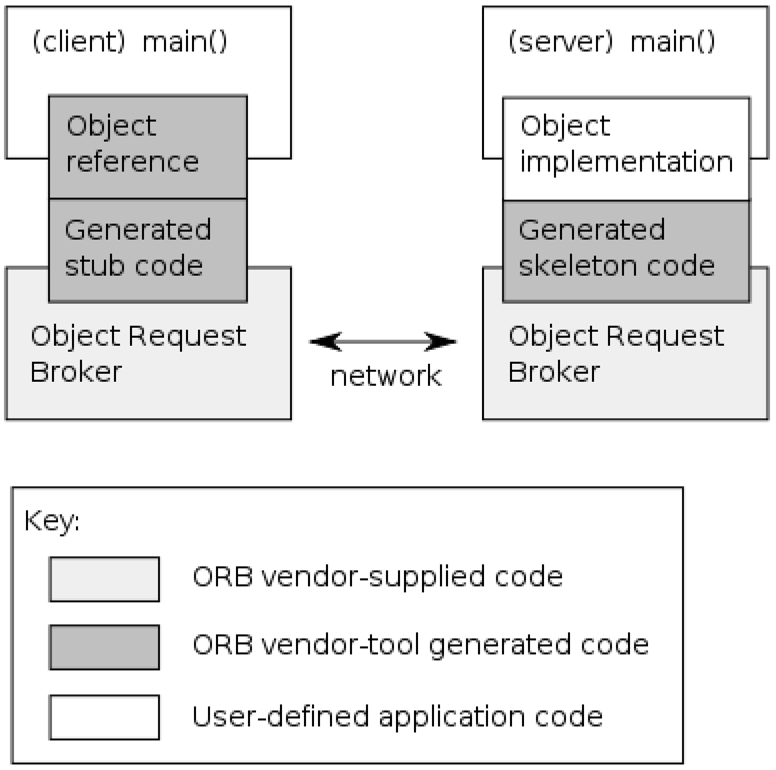


Illustration of the autogeneration of the infrastructure code from an interface defined using the CORBA IDL

This figure illustrates the high-level paradigm for remote interprocess communications using CORBA. Issues not addressed here, yet accounted-for in the CORBA specification include: data typing, exceptions, network protocol, communication timeouts, etc. For example: Normally the server side has the Portable Object Adapter (POA) that redirects calls either to the local servants or (to balance the load) to the other servers. Also, both server and client parts often have interceptors that are described below. Issues CORBA (and thus this figure) does not address, but that all distributed systems must address: object lifetimes, redundancy/fail-over, naming semantics (beyond a simple name), memory management, dynamic load balancing, separation of model between display/data/control semantics, etc.

In addition to providing users with a language and a platform-neutral remote procedure call specification, CORBA defines commonly needed services such as transactions and security, events, time, and other domain-specific interface models.

OMG trademarks

> CORBA, IIOP and OMG are the registered marks of the Object Management Group and should be used with care. However, GIOP is not a registered OMG trademark. Hence in some cases it may be more appropriate just to say that the application uses or implements the GIOP-based architecture.

Objects By Reference

This reference is either acquired through a stringified URI string, NameService lookup (similar to DNS), or passed-in as a method parameter during a call.

Object references are lightweight objects matching the interface of the real object (remote or local). Method calls on the reference result in subsequent calls to the ORB and blocking on the thread while waiting for a reply, success or failure. The parameters, return data (if any), and exception data are marshaled internally by the ORB according the local language and OS mapping.

Data By Value

The CORBA Interface Definition Language provides the language- and OS-neutral inter-object communication definition. CORBA Objects are passed by reference, while data (integers, doubles, structs, enums, etc) are passed by value. The combination of Objects by reference and data-by-value provides the means to enforce strong data typing while compiling clients and servers, yet preserve the flexibility inherent in the CORBA problem-space.

Objects by Value (OBV)

Apart from remote objects, the CORBA and RMI-IIOP define the concept of the OBV and Valuetypes. The code inside the methods of Valuetype objects is executed locally by default. If the OBV has been received from the remote side, the needed code must be either *a priori* known for both sides or dynamically downloaded from the sender. To make this possible, the record, defining OBV, contains the Code Base that is a space-separated list of URLs from where this code should be downloaded. The OBV can also have the remote methods.

The OBV's may have fields that are transferred when the OBV is transferred. These fields can be OBV's themselves, forming lists, trees or arbitrary graphs. The OBV's have a class hierarchy, including multiple inheritance and abstract classes.

CORBA Component Model (CCM)

CORBA Component Model (CCM) is an addition to the family of CORBA definitions. It was introduced with CORBA 3 and it describes a standard application framework for CORBA components. Though not dependent on "language independent Enterprise Java Beans (EJB)", it is a more general form of EJB, providing four component types instead of the two that EJB defines. It provides an abstraction of entities that can provide and accept services through well-defined named interfaces called *ports*.

The CCM has a component container, where software components can be deployed. The container offers a set of services that the components can use. These services include (but are not limited to) notification, authentication, persistence and transaction processing. These are the most-used services any distributed system requires, and, by moving the implementation of these services from the software components to the component container, the complexity of the components is dramatically reduced.

Portable interceptors

Portable interceptors are the "hooks", used by CORBA and RMI-IIOP to mediate the most important functions of the CORBA system. The CORBA standard defines the following types of interceptors:

1. IOR interceptors mediate the creation of the new references to the remote objects, presented by the current server.
2. Client interceptors usually mediate the remote method calls on the client (caller) side. If the object Servant exists on the same server where the method is invoked, they also mediate the local calls.
3. Server interceptors mediate the handling of the remote method calls on the server (handler) side.

The interceptors can attach the specific information to the messages being sent and IORs being created. This information can be later read by the corresponding interceptor on the remote side. Interceptors can also throw forwarding exceptions, redirecting request to another target.

General InterORB Protocol (GIOP)

The GIOP is an abstract protocol by which Object request brokers (ORBs) communicate. Standards associated with the protocol are maintained by the Object Management Group (OMG). The GIOP architecture provides several concrete protocols, including:

1. Internet InterORB Protocol (IIOP) — The Internet Inter-Orb Protocol is an implementation of the GIOP for use over an internet, and provides a mapping between GIOP messages and the TCP/IP layer.
2. SSL InterORB Protocol (SSLIOP) — SSLIOP is IIOP over SSL, providing encryption and authentication.
3. HyperText InterORB Protocol (HTIOP) — HTIOP is IIOP over HTTP, providing transparent proxy bypassing.

VMCID (Vendor Minor Codeset ID)

Each standard CORBA exception includes a minor code to designate the subcategory of the exception. Minor exception codes are of type unsigned long and consist of a 20-bit "Vendor Minor Codeset ID" (VMCID), which occupies the high order 20 bits, and the minor code which occupies the low order 12 bits.

Minor codes for the standard exceptions are prefaced by the VMCID assigned to OMG, defined as the unsigned long constant CORBA::OMGVMCID, which has the VMCID allocated to OMG occupying the high order 20 bits. The minor exception codes associated with the standard exceptions that are found in Table 3-13 on page 3-58 are or-ed with OMGVMCID to get the minor code value that is returned in the ex_body structure.

Within a vendor assigned space, the assignment of values to minor codes is left to the vendor. Vendors may request allocation of VMCIDs by sending email to tagrequest@omg.org.

The VMCID 0 and 0xfffff are reserved for experimental use. The VMCID OMGVMCID (Section 3.17.1, "Standard Exception Definitions," on page 3-52) and 1 through 0xf are reserved for OMG use.

The Common Object Request Broker: Architecture and Specification (CORBA 2.3)

Corba Location (CorbaLoc)

Corba Location (CorbaLoc) refers to a stringified object reference for a CORBA object that looks similar to a URL.

All CORBA products must support two OMG-defined URLs: "`corbaloc:`" and "`corbaname:`". The purpose of these is to provide a human readable and editable way to specify a location where an IOR can be obtained.

An example of corbaloc is shown below:

```
corbaloc::160.45.110.41:38693/StandardNS/NameServer-POA/_root
```

A CORBA product may optionally support the "`http:`", "`ftp:`" and "`file:`" formats. The semantics of these is that they provide details of how to download a stringified IOR (or, recursively, download another URL that will eventually provide a stringified IOR). Some ORBs do deliver additional formats which are proprietary for that ORB.

Benefits

CORBA aims to bring to the table many benefits that no other single technology brings in one package. These benefits include language- and OS-independence, freedom from technology-linked implementations, strong data-typing, high level of tunability, and freedom from the details of distributed data transfers.

Language Independence

CORBA at the outset was designed to free engineers from the hang-ups and limitations of considering their designs based on a particular software language. Currently there are many languages supported by various CORBA providers, the most popular are Java and C++. There are also C-only, SmallTalk, Perl, Ada, Ruby, and Python implementations, just to mention a few.

OS Independence

CORBA's design is meant to be OS-independent. CORBA is available in Java (OS-independent), as well as natively for Linux/Unix, Windows, Sun, Mac and others.

Freedom from Technologies

One of the main implicit benefits is that CORBA provides a neutral playing field for engineers to be able to normalize the interfaces between various new and legacy systems. When integrating C, C++, Object Pascal, Java, Fortran, Python, and any other language or OS into a single cohesive system design model, CORBA provides the means to level the field and allow disparate teams to develop systems and unit tests that can later be joined together into a whole system. This does not rule out the need for basic system engineering decisions, such as threading, timing, object lifetime, etc. These issues are part of any system regardless of technology. CORBA allows system elements to be normalized into a single cohesive system model.

For example, the design of a Multitier architecture is made simple using Java Servlets in the web server and various e time, C++ legacy code can talk to C or Fortran legacy code and Java database code, and can provide data to a web interface.

Strong Data Typing

CORBA provides flexible data typing, for example an "ANY" datatype. CORBA also enforces tightly coupled datatyping, reducing human errors. In a situation where Name-Value pairs are passed around, it's conceivable that a server provides a number where a string was expected. CORBA Interface Definition Language provides the mechanism to ensure that user-code conforms to method-names, return-, parameter-types, and exceptions.

High Tune-ability

There are many implementations available (e.g. OmniORB (Open source C++ and Python implementation)) that have many options for tuning the threading and connection management features. Not all implementations provide the same features. This is up to the implementor.

Freedom From Data Transfer Details

When handling low-level connection and threading, CORBA provides a high level of detail in error conditions. This is defined in the CORBA-defined standard exception set and the implementation-specific extended exception set. Through the exceptions, the application can determine if a call failed for reasons such as "Small problem, so try again", "The server is dead" or "The reference doesn't make sense." The general rule is: Not receiving an exception means that the method call completed successfully. This is a very powerful design feature.

Compression

CORBA marshals its data in a binary form and supports compression. IONA, Remedy IT and Telefónica have worked on an extension to the CORBA standard that delivers compression. This extension is called ZIOP and this is now a formal OMG standard.

Problems and criticism

While CORBA promised to deliver much in the way code was written and software constructed, it has been the subject of much criticism.

Some of the failures were due to the implementations and the process by which CORBA was created as a standard, others reflect problems in the politics and business of implementing a software standard. These problems led to a significant decline in CORBA use and adoption in new projects and areas.

Implementation incompatibilities

The initial specifications of CORBA defined only the IDL, not the on-the-wire format. This meant that source-code compatibility was the best that was available for several years.

Location transparency

CORBA's notion of location transparency has been criticized; that is, that objects residing in the same address space and accessible with a simple function call are treated the same as objects residing elsewhere (different processes on the same machine, or different machines). This notion is flawed if one requires all local accesses to be as complicated as the most complex remote scenario. However, CORBA does not place a restriction on the complexity of the calls. Many implementations provide for recursive thread/connection semantics. I.e. Obj A calls Obj B, which in turn calls Obj A back, before returning.

Design and process deficiencies

The creation of the CORBA standard is also often cited for its process of design by committee. There was no process to arbitrate between conflicting proposals or to decide on the hierarchy of problems to tackle. Thus the standard was created by taking a union of the features in all proposals with no regard to their coherence.

This made the specification very complex, expensive to implement entirely and often ambiguous.

A design committee composed largely of vendors of the standard implementation, created a disincentive to make a comprehensive standard. This was because standards and interoperability increased competition and eased customers' movement between alternative implementations. This led to much political fighting within the committee, and frequent releases of revisions of the CORBA standard that were impossible to use without proprietary extensions.

Problems with implementations

Through its history, CORBA has been plagued by shortcomings in its implementations. Often there have been few implementations matching all of the critical elements of the specification, and existing implementations were incomplete or inadequate. As there were no requirements to provide a reference implementation, members were free to propose features which were never tested for usefulness or implementability. Implementations were further hindered by the general tendency of the standard to be verbose, and the common practice of compromising by adopting the sum of all submitted proposals, which often created APIs that were incoherent and difficult to use, even if the individual proposals were perfectly reasonable.

Working implementations of CORBA have been very difficult to acquire in the past, but are now much easier to find. The SUN Java SDK comes with CORBA already. Some poorly designed implementations have been found to be complex, slow, incompatible and incomplete. Commercial versions can be very expensive. This changed significantly as commercial-, hobbyist-, and government-funded high quality free implementations became available.

Firewalls

CORBA (more precisely, IIOP) uses raw TCP/IP connections in order to transmit data. However, if the client is behind a very restrictive firewall or transparent proxy server environment that only allows HTTP connections to the outside through port 80, communication may be impossible, unless the proxy server in question allows the HTTP CONNECT method or SOCKS connections as well. At one time, it was difficult even to force implementations to use a single standard port — they tended to pick multiple random ports instead. As of today, current ORBs do have these deficiencies. Due to such difficulties, some users have made increasing use of web services instead of CORBA. These communicate using XML/SOAP via port 80, which is normally left open or filtered through a HTTP proxy inside the organization, for web browsing via HTTP. Recent CORBA implementations, though, support SSL and can be easily configured to work on a single port. Most of the popular open source ORBS, such as TAO and JacORB also support bidirectional GIOP, which gives CORBA the advantage of being able to use callback communication rather than the polling approach characteristic of web service implementations. Also, more CORBA-friendly firewalls are now commercially available.

Chapter 13

Component Object Model

Component Object Model (**COM**) is a binary-interface standard for software componentry introduced by Microsoft in 1993. It is used to enable interprocess communication and dynamic object creation in a large range of programming languages. The term *COM* is often used in the Microsoft software development industry as an umbrella term that encompasses the OLE, OLE Automation, ActiveX, COM+ and DCOM technologies.

Overview

The essence of COM is a language-neutral way of implementing objects that can be used in environments different from the one in which they were created, even across machine boundaries. For well-authored components, COM allows reuse of objects with no knowledge of their internal implementation, as it forces component implementers to provide well-defined interfaces that are separate from the implementation. The different allocation semantics of languages are accommodated by making objects responsible for their own creation and destruction through reference-counting. Casting between different interfaces of an object is achieved through the `QueryInterface()` function. The preferred method of inheritance within COM is the creation of sub-objects to which method calls are delegated.

COM is an interface technology defined and implemented as standard only on Microsoft Windows and Apple's Core Foundation 1.3 and later plug-in API , that in any case implement only a subset of the whole COM interface. For some applications, COM has been replaced at least to some extent by the Microsoft .NET framework, and support for Web Services through the Windows Communication Foundation (WCF). However, COM objects can be used with all .NET languages through .NET COM Interop.

Networked DCOM uses binary proprietary formats, while WCF encourages the use of XML-based SOAP messaging. COM is very similar to other component software interface technologies, such as CORBA and Java Beans, although each has its own strengths and weaknesses. The characteristics of COM make it most suitable for the development and deployment of desktop applications, for which it was originally designed.

History

One of the first methods of interprocess communication in Windows was Dynamic Data Exchange (DDE), first introduced in 1987, that allowed sending and receiving messages in so-called "conversations" between applications.

Antony Williams, one of the most notable thinkers involved in the creation of the COM architecture, later distributed two internal papers in Microsoft that embraced the concept of software components: *Object Architecture: Dealing With the Unknown – or – Type Safety in a Dynamically Extensible Class Library* in 1988 and *On Inheritance: What It Means and How To Use It* in 1990. These provided the foundation of many of the ideas behind COM.

Object Linking and Embedding (OLE), Microsoft's first object-based framework, was built on top of DDE and designed specifically for compound documents. It was introduced with Word for Windows and Excel in 1991, and was later included with Windows, starting with version 3.1 in 1992.

An example of a compound document is a spreadsheet embedded in a Word for Windows document: as changes are made to the spreadsheet within Excel, they appear automatically inside the Word document.

In 1991, Microsoft introduced Visual Basic Extensions (VBX) with Visual Basic 1.0. A VBX is a packaged extension in the form of a dynamic-link library (DLL) that allowed objects to be graphically placed in a form and manipulated by properties and methods. These were later adapted for use by other languages such as Visual C++.

In 1993, when version 3.1 of Windows was released, Microsoft released OLE 2 with its underlying object model. The COM Application binary interface (ABI) was the same as the MAPI ABI, which was released in 1992. While OLE 1 was focused on compound documents, COM and OLE 2 were designed to address software components in general. Text conversations and Windows messages had proved not to be flexible enough to allow sharing application features in a robust and extensible way, so COM was created as a new foundation, and OLE changed to OLE2.

In 1994 OLE custom controls (OCXs) were introduced as the successor to VBX controls. At the same time, Microsoft stated that OLE 2 would just be known as "OLE", and that OLE was no longer an acronym, but a name for all of the company's component technologies.

In early 1996, Microsoft found a new use for OLE Custom Controls, expanding their Web browser's capability to present content, renamed some parts of OLE relating to the Internet **ActiveX**, and gradually renamed all OLE technologies to ActiveX, except the compound document technology that was used in Microsoft Office. Later that year, DCOM was introduced as an answer to CORBA.

Related technologies

COM was the major software development platform for Windows and, as such, influenced development of a number of supporting technologies.

COM+

In order for Microsoft to provide developers with support for distributed transactions, resource pooling, disconnected applications, event publication and subscription, better memory and processor (thread) management, as well as to position Windows as an alternative to other enterprise-level operating systems, Microsoft introduced a technology called Microsoft Transaction Server (MTS) on Windows NT 4.

With Windows 2000, that significant extension to COM was incorporated into the operating system (as opposed to the series of external tools provided by MTS) and renamed **COM+**. At the same time, Microsoft de-emphasized DCOM as a separate entity. Components that made use of COM+ services were handled more directly by the added layer of COM+, in particular by operating system support for interception. In the first release of MTS, interception was tacked on - installing an MTS component would modify the Windows Registry to call the MTS software, and not the component directly.

Windows 2000 also revised the Component Services control panel application used to configure COM+ components.

An advantage of COM+ was that it could be run in "component farms". Instances of a component, if coded properly, could be pooled and reused by new calls to its initializing routine without unloading it from memory. Components could also be distributed (called from another machine). COM+ and Microsoft Visual Studio provided tools to make it easy to generate client-side proxies, so although DCOM was used to actually make the remote call, it was easy to do for developers.

COM+ also introduced a subscriber/publisher event mechanism called **COM+ Events**, and provided a new way of leveraging MSMQ (inter-application asynchronous messaging) with components called **Queued Components**. COM+ events extend the COM+ programming model to support late-bound events or method calls between the publisher or subscriber and the event system.

.NET

The COM platform has *largely* been superseded by the Microsoft .NET initiative, and Microsoft now focuses its marketing efforts on *.NET.* COM was often used to hook up complex, high performance code to front end code implemented in Visual Basic or ASP.

To some extent, COM is now deprecated in favor of .NET. Since .NET provides rapid development tools similar to Visual Basic for both Windows Forms and Web Forms with just-in-time compilation, back-end code can be implemented in any .NET Language including C#, Visual Basic and C++/CLI.

Despite this, COM remains a viable technology with an important software base. As of 2009, Microsoft has no plans for discontinuing either COM or support for COM. It is also ideal for script control of applications such as Office or Internet Explorer since it provides an interface for calling COM object methods from a script rather than requiring knowing the API at compile time. The GUID system used by COM has wide uses any time a unique ID is needed.

Several of the services that COM+ provides have been largely replaced by recent releases of .NET. For example, the System.Transactions namespace in .NET provides the TransactionScope class, which provides transaction management without resorting to COM+. Similarly, queued components can be replaced by Windows Communication Foundation with an MSMQ transport.

There is limited support for backward compatibility. A COM object may be used in .NET by implementing a *runtime callable wrapper* (RCW). .NET objects that conform to certain interface restrictions may be used in COM objects by calling a *COM callable wrapper* (CCW). From both the COM and .NET sides, objects using the other technology appear as native objects.

WCF solves a number of COM's remote execution shortcomings, allowing objects to be transparently marshalled by value across process or machine boundaries.

Internet security

Microsoft's idea of embedding active content on web pages as COM/ActiveX components (rather than e.g. Java applets) created a combination of problems in the Internet Explorer web browser that has led to an explosion of computer virus, trojan and spyware infections. These malware attacks mostly depend on ActiveX for their activation and propagation to other computers. Microsoft recognized the problem with ActiveX as far back as 1996 when Charles Fitzgerald, program manager of Microsoft's Java team said "If you want security on the 'Net', unplug your computer. … We never made the claim up front that ActiveX is intrinsically secure."

As COM and ActiveX components are run as native code on the user's machine, there are fewer restrictions on what the code can do. Many of these problems have been addressed by the introduction of "Authenticode" code signing (based on digital signatures), and later by the .NET platform also. Another security measure is that, before an ActiveX control is installed, the user is prompted whether to allow the installation or not, enabling the user to disallow the installation of controls from sites that the user does not trust. It is also possible to disable ActiveX controls altogether, or to allow only a selected few.

Technical details

COM programmers build their software using COM-aware components. Different component types are identified by class IDs (CLSIDs), which are Globally Unique Identifiers (GUIDs). Each COM component exposes its functionality through one or more interfaces. The different interfaces supported by a component are distinguished from each other using interface IDs (IIDs), which are GUIDs too.

COM interfaces have bindings in several languages, such as C, C++, Visual Basic, Delphi, and several of the scripting languages implemented on the Windows platform. All access to components is done through the methods of the interfaces. This allows techniques such as inter-process, or even inter-computer programming (the latter using the support of DCOM).

Interfaces

All COM components must (at the very least) implement the standard `IUnknown` interface, and thus all COM interfaces are derived from `IUnknown`. The `IUnknown` interface consists of three methods: `AddRef()` and `Release()`, which implement reference counting and controls the lifetime of interfaces; and `QueryInterface()`, which by specifying an IID allows a caller to retrieve references to the different interfaces the component implements. The effect of `QueryInterface()` is similar to `dynamic_cast<>` in C++ or casts in Java and C#.

A COM component's interfaces are required to exhibit the reflexive, symmetric, and transitive properties. The reflexive property refers to the ability for the `QueryInterface()` call on a given interface with the interface's ID to return the same instance of the interface. The symmetric property requires that when interface B is retrieved from interface A via `QueryInterface()`, interface A is retrievable from interface B as well. The transitive property requires that if interface B is obtainable from interface A and interface C is obtainable from interface B, then interface C should be retrievable from interface A.

An interface consists of a pointer to a virtual function table that contains a list of pointers to the functions that implement the functions declared in the interface, in the same order that they are declared in the interface. This technique of passing structures of function pointers is very similar to the one used by OLE 1.0 to communicate with its system libraries.

COM specifies many other standard interfaces used to allow inter-component communication. For example, one such interface is `IStream`, which is exposed by components that have data stream semantics (e.g. a `FileStream` component used to read or write files). It has the expected `Read` and `Write` methods to perform stream reads and writes. Another standard interface is `IOleObject`, which is exposed by components that expect to be linked or embedded into a container. `IOleObject` contains methods that allow callers to determine the size of the component's bounding rectangle, whether the component supports operations like 'Open', 'Save' and so on.

Classes

A class is COM's language-independent way of defining a class in the object-oriented sense.

A class can be a group of similar objects or a class is simply a representation of a type of object; it should be thought of as a blueprint that describes the object.

A coclass supplies **concrete** implementation(s) of one or more interfaces. In COM, such concrete implementations can be written in any programming language that supports COM component development, e.g. Delphi, C++, Visual Basic, etc.

One of COM's major contributions to the world of Windows development is the awareness of the concept of **separation of interface from implementation**. An extension of this fundamental concept is the notion of **one interface, multiple implementations**. This means that at runtime, an application can choose to instantiate an interface from one of many different concrete implementations.

Interface Definition Language and type libraries

Type libraries contain metadata that represent COM types. However, these types must first be described using Microsoft Interface Definition Language.

This is the common practice in the development of a COM component, i.e. to start with the definition of types using **IDL.** An IDL file is what COM provides that allows developers to define object-oriented classes, interfaces, structures, enumerations and other user-defined types in a language independent manner. COM IDL is similar in appearance to C/C++ declarations with the addition of keywords such as "interface" and "library" for defining interfaces and collections of classes, respectively. IDL also requires the use of bracketed attributes before declarations to provide additional information, such as the GUIDs of interfaces and the relationships between pointer parameters and length fields.

The IDL file is compiled by the MIDL compiler into a pair of forms for consumption from various languages. For C/C++, the MIDL compiler generates a compiler-independent header file containing struct definitions to match the vtbls of the declared interfaces and a C file containing declarations of the interface GUIDs. C++ source code for a proxy module can also be generated by the MIDL compiler. This proxy contains method stubs for converting COM calls into Remote Procedure Calls, thus enabling DCOM.

An IDL file may also be compiled by the MIDL compiler into a type library (.TLB file). The binary metadata contained within the type library is meant to be processed by language compilers and runtime environments (e.g. VB, Delphi, the .NET CLR etc.). The end result of such TLB processing is that language-specific constructs are produced that represent the COM class defined in the .TLB (and ultimately that which was defined in the originating IDL file).

COM as an object framework

The fundamental principles of COM have their roots in Object-Oriented philosophies. It is a platform for the realization of Object-Oriented Development and Deployment.

Because COM is a runtime framework, types have to be individually identifiable and specifiable at runtime. To achieve this, **globally unique identifiers** (**GUIDs**) are used. Each COM type is designated its own GUID for identification at runtime (versus compile time).

In order for information on COM types to be accessible at both compile time and runtime, COM uses type libraries. It is through the effective use of type libraries that COM achieves its capabilities as a dynamic framework for the interaction of objects.

Consider the following example coclass definition in an IDL :

```
coclass MyObject
{
  [default] interface IMyObject;
  [default, source] dispinterface _IMyObjectEvents;
};
```

The above code fragment declares a COM class named MyObject which must implement an interface named IMyObject and which supports (not implements) the event interface _IMyObjectEvents.

Ignoring the event interface bit, this is conceptually equivalent to defining a C++ class like this:

```
class CSomeObject : public ISomeInterface
{
  ...
  ...
  ...
};
```

where ISomeInterface is a C++ pure virtual class.

Referring once again to the MyObject COM class: once a coclass definition for it has been formalized in an IDL, and a Type Library compiled from it, the onus is on the individual language compiler to read and appropriately interpret this Type Library and then produce whatever code (in the specific compiler's language) necessary for a developer to implement and ultimately produce the binary executable code which can be deemed by COM to be of coclass MyObject.

Once an implementation of a COM coclass is built and is available in the system, next comes the question of how to instantiate it. In languages like C++, we can use the CoCreateInstance() API in which we specify the CLSID (CLSID_MyObject) of the coclass as well as the interface (specified by the IID IID_IMyObject) from that coclass that we want to use to interact with that coclass. Calling CoCreateInstance() like this:

```
CoCreateInstance(CLSID_MyObject,
    NULL,
    CLSCTX_INPROC_SERVER,
    IID_IMyObject,
    (void**)&m_pIMyObject);
```

is conceptually equivalent to the following C++ code:

```
ISomeInterface* pISomeInterface = new CSomeObject();
```

In the first case, the COM sub-system is used to obtain a pointer to an object that implements the IMyObject interface and coclass CLSID_MyObject's particular implementation of this interface is required. In the second case, an instance of a C++ class CSomeObject that implements the interface ISomeInterface is created.

A coclass, then, is an object-oriented class in the COM world. The main feature of the coclass is that it is (1) binary in nature and consequently (2) programming language-independent.

Registry

In Windows, COM classes, interfaces and type libraries are listed by GUIDs in the registry, under HKEY_CLASSES_ROOT\CLSID for classes and HKEY_CLASSES_ROOT\Interface for interfaces. The COM libraries use the registry to locate either the correct local libraries for each COM object or the network location for a remote service.

Under the key HKCR\clsid, the following are specified:

```
-> Inprocserver32 =  object is to be
              loaded into a process        +
       Path to file/object and readable name
HKCR\interface:
 example:  ISTREAM, IRPCSTUB, IMESSAGEFILTER
   connects to a CLSID. You can specify
   NUMMETHODS and PROXYSTUB(if web-object)

HKCR\typelib
  One or more CLSID can be grouped into type library.
  it contains parameters for linking in COM.
 The rest of the info in the COM parts of the
  REGISTRY, is to give an application/object
   a CLSID.
```

Reference counting

The most fundamental COM interface of all, IUnknown (from which all COM interfaces must be derived), supports two main concepts: feature exploration through the **QueryInterface** method, and object lifetime management by including **AddRef()** and **Release()**. Reference counts and feature exploration apply to objects (not to each interface on an object) and thus must have a centralized implementation.

The COM specifications require a technique called reference counting to ensure that individual objects remain alive as long as there are clients which have acquired access to one or more of its interfaces and, conversely, that the same object is properly disposed of when all code that used the object have finished with it and no longer require it. A COM object is responsible for freeing its own memory once its reference count drops to zero.

For its implementation, a COM Object usually maintains an integer value that is used for reference counting. When AddRef() is called via any of object's interfaces, this integer value is incremented. When Release() is called, this integer is decremented. AddRef() and Release() are the only means by which a client of a COM object is able to influence its lifetime. The internal integer value remains a private member of the COM object and will never be directly accessible.

The purpose of AddRef() is to indicate to the COM object that an additional reference to itself has been affected and hence it is necessary to remain alive as long as this reference is still valid. Conversely, the purpose of Release() is to indicate to the COM object that a client (or a part of the client's code) has no further need for it and hence if this reference count has dropped to zero, it may be time to destroy itself.

Certain languages (e.g. Visual Basic) provide automatic reference counting so that COM object developers need not explicitly maintain any internal reference counter in their source codes. Using COM in C, explicit reference counting is needed. In C++, a coder may write the reference counting code or use a smart pointer that will manage all the reference counting.

The following is a general guideline calling AddRef() and Release() to facilitate proper reference counting in COM object:

- Functions (whether object methods or global functions) that return interface references (via return value or via "out" parameter) should increment the reference count of the underlying object before returning. Hence internally within the function or method, AddRef() is called on the interface reference (to be returned). An example of this is the QueryInterface() method of the IUnknown interface. Hence it is imperative that developers be aware that the returned interface reference has already been reference count incremented and not call AddRef() on the returned interface reference yet another time.

- Release() must be called on an interface reference before that interface's pointer is overwritten or goes out of scope.
- If a copy is made on an interface reference pointer, AddRef() should be called on that pointer. After all, in this case, we are actually creating another reference on the underlying object.
- AddRef() and Release() must be called on the specific interface which is being referenced since an object may implement per-interface reference counts in order to allocate internal resources only for the interfaces which are being referenced.
- Extra calls to these functions are not sent out to remote objects over the wire; a proxy keeps only one reference on the remote object and maintains its own local reference count.

To facilitate and promote COM development, Microsoft introduced ATL (Active Template Library) for C++ developers. ATL provides for a higher-level COM development paradigm. It also shields COM client application developers from the need to directly maintain reference counting, by providing smart pointer objects.

Other libraries and languages that are COM-aware include the Microsoft Foundation Classes, the VC Compiler COM Support, VBScript, Visual Basic, ECMAScript (JavaScript) and Borland Delphi.

Instantiation

COM standardizes the instantiation (i.e. creation) process of COM objects by requiring the use of **Class Factories**. In order for a COM object to be created, two associated items must exist:

- A Class ID.
- A Class Factory.

Each COM Class or **CoClass** must be associated with a unique Class ID (a GUID). It must also be associated with its own Class Factory (that is achieved by using a centralized registry). A Class Factory is itself a COM object. It is an object that must expose the IClassFactory or IClassFactory2 (the latter with licensing support) interface. The responsibility of such an object is to create other objects.

A class factory object is usually contained within the same executable code (i.e. the **server code**) as the COM object itself. When a class factory is called upon to create a target object, this target object's class id must be provided. This is how the class factory knows which class of object to instantiate.

A single class factory object may create objects of more than one class. That is, two objects of different class ids may be created by the same class factory object. However, this is transparent to the COM system.

By delegating the responsibility of object creation into a separate object, a greater level of abstraction is promoted, and the developer is given greater flexibility. For example, implementation of the **Singleton** and other creation patterns is facilitated. Also, the calling application is shielded from the COM object's memory allocation semantics by the factory object.

In order for client applications to be able to acquire class factory objects, COM servers must properly expose them. A class factory is exposed differently, depending on the nature of the server code. A server which is DLL-based must export a **DllGetClassObject()** global function. A server which is EXE-based registers the class factory at runtime via the **CoRegisterClassObject()** Windows API function.

The following is a general outline of the sequence of object creation via its class factory:

1. The object's class factory is obtained via the **CoGetClassObject()** API (a standard Windows API).
   As part of the call to CoGetClassObject(), the Class ID of the object (to be created) must be supplied. The following C++ code demonstrates this:

```
IClassFactory* pIClassFactory = NULL;

CoGetClassObject(CLSID_SomeObject,
    CLSCTX_ALL,
    NULL,
    IID_IClassFactory,
    (LPVOID*)&pIClassFactory);
```

   The above code indicates that the Class Factory object of a COM object, which is identified by the class id CLSID_SomeObject, is required. This class factory object is returned by way of its IClassFactory interface.

9. The returned class factory object is then requested to create an instance of the originally intended COM object. The following C++ code demonstrates this:

```
ISomeObject* pISomeObject = NULL;

if (pIClassFactory)
{
    pIClassFactory->CreateInstance (NULL,
        IID_ISomeObject,
        (LPVOID*)&pISomeObject);

    pIClassFactory->Release();

    pIClassFactory = NULL;
}
```

   The above code indicates the use of the Class Factory object's **CreateInstance()** method to create an object which exposes an interface identified by the IID_ISomeObject GUID. A pointer to the ISomeObject interface of this object is returned. Also note that because the class factory object is itself a COM object, it needs to be released when it is no longer required (i.e. its **Release()** method must be called).

The above demonstrates, at the most basic level, the use of a class factory to instantiate an object. Higher level constructs are also available, some of which do not even involve direct use of the Windows APIs.

For example, the **CoCreateInstance()** API can be used by an application to directly create a COM object without acquiring the object's class factory. However, internally, the CoCreateInstance() API itself will invoke the CoGetClassObject() API to obtain the object's class factory and then use the class factory's CreateInstance() method to create the COM object.

VBScript supplies the **New** keyword as well as the **CreateObject()** global function for object instantiation. These language constructs encapsulate the acquisition of the class factory object of the target object (via the CoGetClassObject() API) followed by the invocation of the IClassFactory::CreateInstance() method.

Other languages, e.g. PowerBuilder's PowerScript may also provide their own high-level object creation constructs. However, CoGetClassObject() and the IClassFactory interface remain the most fundamental object creation technique.

Reflection

At the time of the inception of COM technologies, the only way for a client to find out what features an object would offer was to actually create one instance and call into its QueryInterface method (part of the required IUnknown interface). This way of exploration became awkward for many applications, including the selection of appropriate components for a certain task, and tools to help a developer understand how to use methods provided by an object.

As a result, COM Type Libraries were introduced, through which components can describe themselves. A type library contains information such as the CLSID of a component, the IIDs of the interfaces the component implements, and descriptions of each of the methods of those interfaces. Type libraries are typically used by Rapid Application Development (RAD) environments such as Visual Basic or Visual Studio to assist developers of client applications.

Programming

COM is a binary standard (also said to be **language agnostic**) and may be developed in any programming language capable of understanding and implementing its binary defined data types and interfaces.

Runtime libraries (in extreme situations, the programmers) are responsible for entering and leaving the COM environment, instantiating and reference counting COM objects, querying objects for version information, coding to take advantage of advanced object versions, and coding graceful degradation of function when newer versions are not available.

Application and network transparency

COM objects may be instantiated and referenced from within a process, across process boundaries within a computer, and across a network, using the DCOM technology. Out-of-process and remote objects may use marshalling to send method calls and return values back and forth. The marshalling is invisible to the object and the code using the object.

Threading in COM

In COM, threading issues are addressed by a concept known as "**apartment models**". Here the term "**apartment**" refers to an execution context wherein a single thread or a group of threads is associated with one or more **COM objects**.

Apartments stipulate the following general guidelines for participating threads and objects:

- Each COM object is associated with one and only one apartment. This is decided at the time the object is created at runtime. After this initial setup, the object remains in that apartment throughout its lifetime.
- A COM thread (i.e., a thread in which COM objects are created or COM method calls are made) is also associated with an apartment. Like COM objects, the apartment with which a thread is associated is also decided at initialization time. Each COM thread also remains in its designated apartment until it terminates.
- Threads and objects which belong to the same apartment are said to follow the same thread access rules. Method calls which are made inside the same apartment are performed directly without any assistance from COM.
- Threads and objects from different apartments are said to play by different thread access rules. Method calls made across apartments are achieved via marshalling. This requires the use of proxies and stubs.

There are three types of Apartment Models in the COM world: **Single-Threaded Apartment (STA)**, **Multi-Threaded Apartment (MTA)**, and **Neutral Apartment**. Each apartment represents one mechanism whereby an object's internal state may be synchronized across multiple threads.

The Single-Threaded Apartment (STA) model is a very commonly used model. Here, a COM object stands in a position similar to a desktop application's user interface. In an STA model, a single thread is dedicated to drive an object's methods, i.e. a single thread is always used to execute the methods of the object. In such an arrangement, method calls from threads outside of the apartment are marshalled and automatically queued by the system (via a standard Windows message queue). Thus, there is no worry about race conditions or lack of synchronicity because each method call of an object is always executed to completion before another is invoked.

If the COM object's methods perform their own synchronization, multiple threads dedicated to calling methods on the COM object are permitted. This is termed the Multiple Threaded Apartment (MTA). Calls to an MTA object from a thread in an STA are also marshaled. A process can consist of multiple COM objects, some of which may use STA and others of which may use MTA. The Thread Neutral Apartment allows different threads, none of which is necessarily dedicated to calling methods on the object, to make such calls. The only provision is that all methods on the object must be serially reentrant.

Criticisms

Since COM has a fairly complex implementation, programmers can be distracted by some of the "plumbing" issues.

Message pumping

When an STA is initialized it creates a hidden window that is used for inter-apartment and inter-process message routing. This window must have its message queue regularly pumped. This construct is known as a message pump. On earlier versions of Windows, failure to do so could cause system-wide deadlocks. This problem is especially nasty because some Windows APIs initialize COM as part of their implementation, which causes a leak of implementation details.

Reference counting

Reference counting within COM may cause problems if two or more objects are circularly referenced. The design of an application must take this into account so that objects are not left orphaned.

Objects may also be left with active reference counts if the COM "event sink" model is used. Since the object that fires the event needs a reference to the object reacting to the event, the object's reference count will never reach zero.

Reference cycles are typically broken using either out-of-band termination or split identities. In the out of band termination technique, an object exposes a method which, when called, forces it to drop its references to other objects, thereby breaking the cycle. In the split identity technique, a single implementation exposes two separate COM objects (also known as identities). This creates a weak reference between the COM objects, preventing a reference cycle.

DLL hell

Because the location of each component is stored in a system-wide location (the Windows registry), there can be only one version of a certain component installed. This limitation can seriously complicate the deployment of COM-based applications, due to the possibility that different programs, or even different versions of the same program, may be designed to work with different versions of the same COM component. This condition is known as DLL hell. While this condition has been known to occur with OS components, it is generally a condition created by application developers in the use of their own components. The problem can be reduced or eliminated completely by careful software versioning and regression testing.

Windows XP introduced a new mode of COM object registration called "**Registration-free COM**". This facility makes it possible for applications that need to install COM objects to store all the required COM registry information in the application's directory, instead of in the global registry, so that, strictly speaking, only that application will ever see/use it. DLL hell can be substantially avoided using Registration-free COM, the only limitation being it requires at least Windows XP or later Windows versions and that it must not be used for EXE COM servers or system-wide components such as MDAC, MSXML, DirectX or Internet Explorer.

RegFree COM

RegFree COM (or **Registration-Free COM**) is a technology introduced with Windows XP that allows Component Object Model (COM) components to store activation metadata and CLSID (`Class ID`) for the component without using the registry. Instead, the metadata and CLSIDs of the classes implemented in the component are declared in an assembly manifest (described using XML), stored either as a resource in the executable or as a separate file installed with the component. This allows multiple versions of the same component to be installed in different directories, described by their own manifests, as well as XCOPY deployment.

During application loading, the Windows loader searches for the manifest. If it is present, the loader adds information from it to the activation context When the COM class factory tries to instantiate a class, the activation context is first checked to see if an implementation for the CLSID can be found. Only if the lookup fails is the registry scanned.

Chapter 14

Dependency Injection

Dependency injection (**DI**) in object-oriented computer programming is a technique that indicates to a part of a program which other parts it can use, i.e. to supply an external dependency (i.e. a reference) to a software component. In technical terms, it is a design pattern that separates behavior from dependency resolution, thus decoupling highly dependent components.

Developers of software strive to reduce dependencies between components in software for various reasons. This leads to a new problem, though: How can a component know all the other components it needs to fulfill its purpose?

The traditional approach was to hard-code the dependency. As soon as the database driver was necessary, the component would execute a piece of code that would load a specific driver, configure it and call the necessary methods to interact with the database. If a second database must be supported, this piece of code would have to be modified or, even worse, copied and modified (violating the DRY principle).

Dependency injection offers a solution. Instead of hard-coding the dependencies, a component just lists the necessary services and a DI framework supplies these. At runtime, an independent component will load and configure the database driver and offer a standard interface to interact with the database. Again, the details have been moved from the original component to a set of new, small, database specific components, reducing the complexity of them all.

In DI terms, these new components are called "service components" because they render a service (database access) for one or more other components.

Dependency injection is a specific form of inversion of control where the concern being inverted is the process of obtaining the needed dependency. The term was first coined by Martin Fowler to describe the mechanism more clearly.

Basics

Without dependency injection, a consumer component that needs a particular service in order to accomplish a task will depend not only on the interface of the service but also on the details of a particular implementation of that service. The user component has to handle both its use of the service and the life-cycle of that service - creating an instance, opening and closing streams, disposing of unneeded objects, etc.

Using dependency injection, however, the life-cycle of a service is handled by a dependency provider rather than the consumer. The dependency provider is an independent, external component that links the consuming component and the providing component. The consumer would thus only need a reference to an implementation of the service that it needed in order to accomplish the necessary task.

Such a pattern involves at least three elements: a **dependent** consumer, the definition of its service **dependencies,** and an **injector** (sometimes referred to as a **provider** or **container**). The dependent is a consumer component that needs to accomplish a task in a computer program. In order to do so, it needs the help of various services (the dependencies) that execute certain sub-tasks. The provider is the component that is able to compose the dependent and its dependencies so that they are ready to be used, while also managing these objects' life-cycles. The provider may be implemented, for example, as a service locator, an abstract factory, a factory method or a more complex abstraction such as a framework.

The following is an example. A car (the consumer) depends upon an engine (the dependency) in order to move. The car's engine is made by an automaker (the dependency provider). The car does not know how to install an engine into itself, but it needs an engine in order to move. The automaker installs an engine into the car and the car utilizes the engine to move.

When the concept of dependency injection is used, it decouples high-level modules from low-level services. The result is called the dependency inversion principle.

Code illustration using Java

Using the car/engine example above mentioned, the following Java examples show how coupled dependencies (manually-injected dependencies) and framework-injected dependencies are typically staged.

```
public interface Engine {
    public float getEngineRPM();

    public void setFuelConsumptionRate(float flowInGallonsPerMinute);
}

public interface Car {
    public float getSpeedInMPH();

    public void setPedalPressure(float pedalPressureInPounds);
}
```

Highly coupled dependency

The following shows a common arrangement **with no dependency injection applied**:

```
public class DefaultEngineImpl implements Engine {
    private float engineRPM = 0;

    public float getEngineRPM() {
        return engineRPM;
    }

    public void setFuelConsumptionRate(float flowInGallonsPerMinute) {
        engineRPM = ...;
    }
}

public class DefaultCarImpl implements Car {
    private Engine engine = new DefaultEngineImpl();

    public float getSpeedInMPH() {
        return engine.getEngineRPM() * ...;
    }

    public void setPedalPressure(float pedalPressureInPounds) {
        engine.setFuelConsumptionRate(...);
    }
}

public class MyApplication {
    public static void main(String[] args) {
        Car car = new DefaultCarImpl();
        car.setPedalPressure(5);
        float speed = car.getSpeedInMPH();
    }
}
```

In the above example, the `Car` class creates an instance of an `Engine` implementation in order to perform operations on the car. Hence, it is considered highly coupled because it couples a car directly with a particular engine implementation.

In cases where the `DefaultEngineImpl` dependency is managed outside of the scope of the `Car` class, the `Car` class must not instantiate the `DefaultEngineImpl` dependency. Instead, that dependency is injected externally.

Manually-injected dependency

Refactoring the above example to use manual injection:

```
public class DefaultCarImpl implements Car {
    private Engine engine;

    public DefaultCarImpl(Engine engineImpl) {
        engine = engineImpl;
    }

    public float getSpeedInMPH() {
        return engine.getEngineRPM() * ...;
    }

    public void setPedalPressure(float pedalPressureInPounds) {
        engine.setFuelConsumptionRate(...);
    }
}

public class CarFactory {
    public static Car buildCar() {
        return new DefaultCarImpl(new DefaultEngineImpl());
    }
}

public class MyApplication {
    public static void main(String[] args) {
        Car car = CarFactory.buildCar();
        car.setPedalPressure(5);
        float speed = car.getSpeedInMPH();
    }
}
```

In the example above, the `CarFactory` class assembles a car and an engine together by injecting a particular engine implementation into a car. This moves the dependency management from the `Car` class into the `CarFactory` class. As a consequence, if the `Car` needed to be assembled with a different `Engine` implementation, the `Car` code would not be changed.

In a more realistic software application, this may happen if a new version of a base application is constructed with a different service implementation. Using factories, only the service code and the Factory code would need to be modified, but not the code of the multiple users of the service.

However, this still may not be enough abstraction for some applications, since in a realistic application there would be multiple Factory classes to create and update.

Framework-managed dependency injection

There are several frameworks available that automate dependency management by delegating the management of dependencies. Typically, this is accomplished by a Container using XML or "meta data" definitions. Refactoring the above example to use an external XML-definition framework:

```
    <service-point id="CarBuilderService">
        <invoke-factory>
            <construct class="Car">
                <service>DefaultCarImpl</service>
                <service>DefaultEngineImpl</service>
            </construct>
        </invoke-factory>
    </service-point>
/** Implementation not shown **/

public class MyApplication {
    public static void main(String[] args) {
        Service service =
(Service)DependencyManager.get("CarBuilderService");
        Car car = (Car)service.getService(Car.class);
        car.setPedalPressure(5);
        float speed = car.getSpeedInMPH();
    }
}
```

In the above example, a dependency injection service is used to retrieve a `CarBuilderService` service. When a Car is requested, the service returns an appropriate implementation for both the car and its engine.

As there are many ways to implement dependency injection, only a small subset of examples is shown herein. Dependencies can be registered, bound, located, externally injected, etc., by many different means. Hence, moving dependency management from one module to another can be accomplished in a plethora of ways. However, there should exist a definite reason for moving a dependency away from the object that needs it because doing so can complicate the code hierarchy to such an extent that its usage appears to be "magical". For example, suppose a Web container is initialized with an association between two dependencies and that a user who wants to use one of those dependencies is unaware of the association. The user would thus not be able to detect any linkage between those dependencies and hence might cause drastic problems by using one of those dependencies.

Benefits and drawbacks

One benefit of using the dependency injection approach is the reduction of boilerplate code in the application objects since all work to initialize or set up dependencies is handled by a provider component.

Another benefit is that it offers configuration flexibility because alternative implementations of a given service can be used without recompiling code. This is useful in unit testing because it is easy to inject a fake implementation of a service into the object being tested by changing the configuration file.

One drawback is that excessive or inappropriate use of dependency injection can make applications more complicated, harder to understand and more difficult to modify. Code that uses dependency injection can seem *magical* to some developers, since instantiation and initialization of objects is handled completely separately from the code that uses it. This separation can also result in problems that are hard to diagnose. Additionally, some dependency injection frameworks maintain verbose configuration files, requiring that a developer understand the configuration as well as the code in order to change it.

Another drawback is that some IDEs might not be able to accurately analyze or refactor code when configuration is "invisible" to it. Some IDEs mitigate this problem by providing explicit support for various frameworks. Additionally, some frameworks provide configuration using the programming language itself, allowing refactoring directly. Other frameworks, such as the Grok web framework, introspect the code and use convention over configuration as an alternative form of deducing configuration information. For example, if a Model and View class were in the same module, then an instance of the View will be created with the appropriate Model instance passed into the constructor-

Criticisms

A criticism of dependency injection is that it is simply a re-branding of existing object-oriented design concepts. The examples typically cited (including the one above) simply show how to fix bad code, not a new programming paradigm. Offering constructors and/or setter methods that take interfaces, relieving the implementing class from having to choose an implementation, is an idea that was rooted in object-oriented programming long before Martin Fowler's article or the creation of any of the recent frameworks that champion it.

Types

Fowler identifies three ways in which an object can get a reference to an external module, according to the pattern used to provide the dependency:

- *Type 1* or *interface injection*, in which the exported module provides an interface that its users must implement in order to get the dependencies at runtime.
- *Type 2* or *setter injection*, in which the dependent module exposes a setter method that the framework uses to inject the dependency.
- *Type 3* or *constructor injection*, in which the dependencies are provided through the class constructor.

It is possible for other frameworks to have other types of injection, beyond those presented above.