DEFENCE R&D DÉFENSE

Software Vulnerabilities & Verification Tools for C/C++ and Java

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Introduction

- Building reliable and secure software is a difficult task
  - Unmanageable complexity is the main problem
- Flaws have many origins
  - **Design** (ex: backdoor)
  - **Implementation** (ex: buffer overrun)
  - …

Context

- Sensitive but not safety-critical applications
- Built with familiar technologies that users want
    - Windows, Linux, C++, Java
- Our goal:
    – Get rid of common security problems using automated source code verification tools
- Design flaws:
    – *C2 Secure Design Patterns Study (04-05)*
- Implementation flaws:
    – ***Verification tools study (05-06)***

Goals of this Project

- Identify common software defects related to C/C++ and Java usage
  - Non application-specific
- Investigate errors and vulnerabilities created by these defects
- Evaluate best of breed automatic verification tools for C/C++ and Java
  - Defect & error detection performance
  - Usability
- Infer best practices

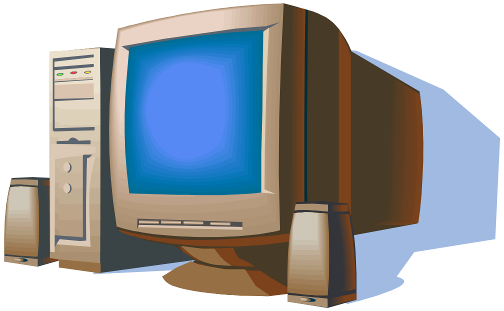
Plan of the Presentation

1. **Terminology**
2. Errors
3. Vulnerabilities
4. Pitfalls & Shortcomings of C/C++
5. Defects
6. Tools Overview
7. Evaluation
8. Conclusion

Program Sanity vs. Security

- **Program Sanity**
  - Low level rules/conventions
  - E.g.: C calling convention & parameters placement on the stack
  - Mostly related to programming
- **Security**
  - High level control mechanisms
  - For confidentiality, integrity and availability
  - Mostly related to design

Program Sanity vs. Security



Program Sanity	Security
• Protected memory	• Access Control
• Valid control flow	• Anti-virus
• Valid data flow	• Intrusion Prevention Systems
• Correct management of resources	• Firewall

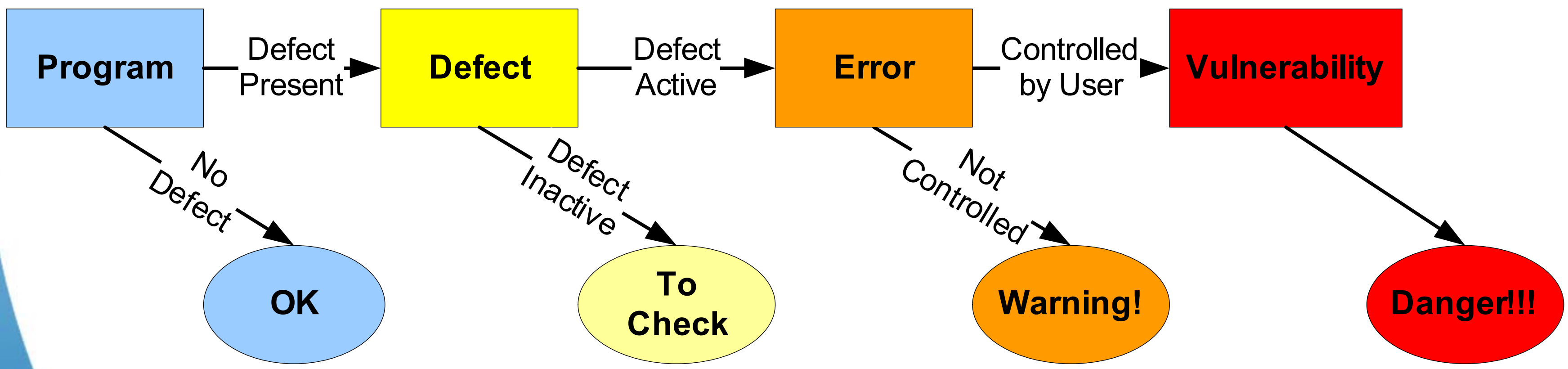
Program Sanity vs. Security

- Automatic detection of security problems
  - Too much variability
  - Too much complexity
- Automatic detection of program sanity problems
  - More or less always the same thing
  - Especially interesting for C/C++
- Security begins with program sanity
  - **Program sanity problems are the main cause of software security problems**

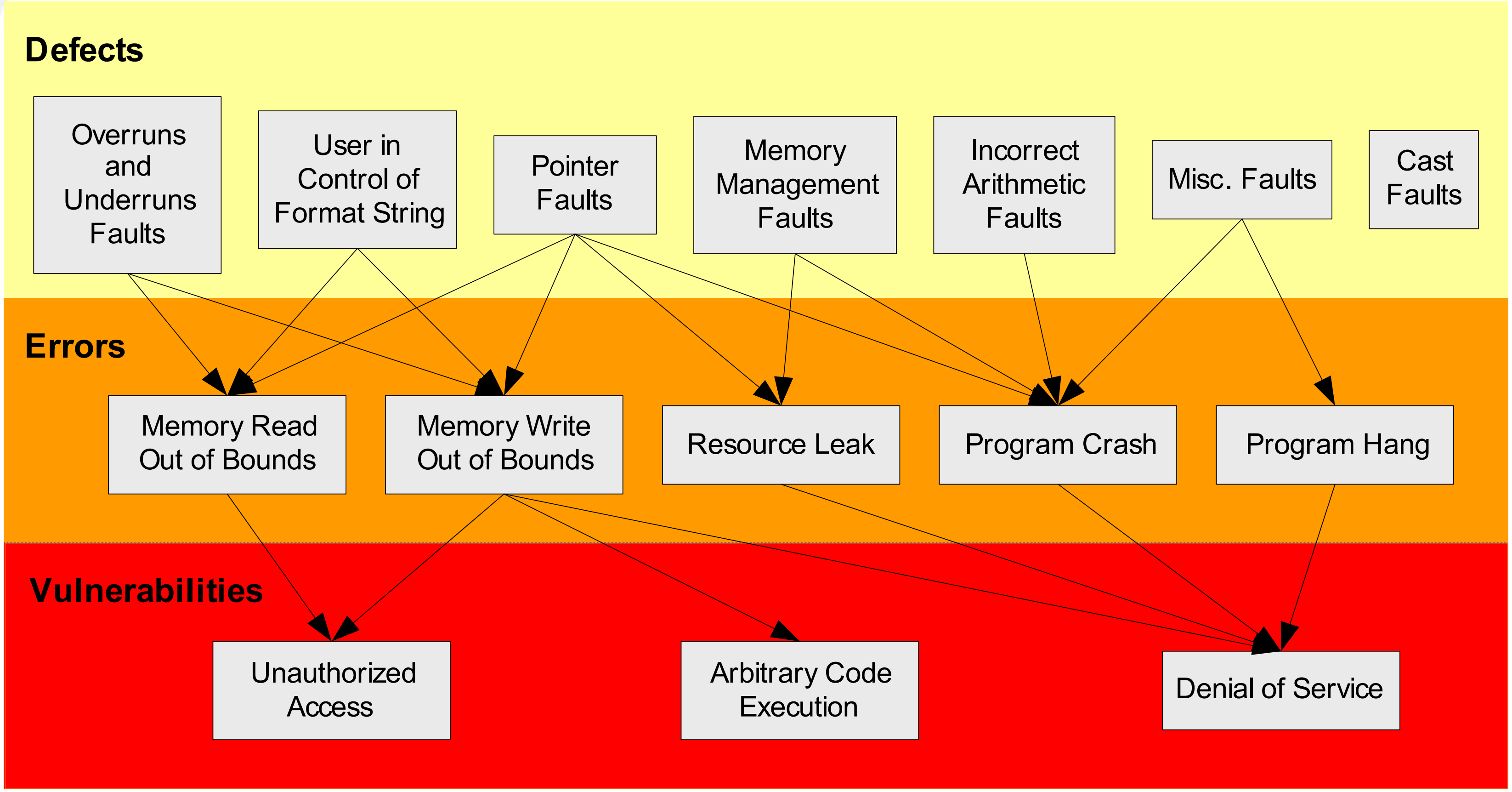
Some Terminology

- Error → Execution
  - Event that occurs when the behavior of a program diverges from "what it should be"
- Defect → Code
  - Cause of an error, a set of program instructions
  - Can be the lack of something
- Vulnerability → Exploitation
  - Defect allowing a user to control the program execution when it should not

Defects, Errors and Vulnerabilities



Defects, Errors and Vulnerabilities



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Errors

- The list of possible low-level problems is almost endless
  - No interest in the correctness of computations with respect to specifications
- Correct low-level program execution
  - Memory access
  - Control flow
  - Resource allocation
- Java is immune to most program sanity problems

Memory Write Out of Bounds

- A region of valid memory is overwritten
- Impacts
  - Depends on what is overwritten
  - **Can lead to many serious vulnerabilities**
- Causes
  - Bad pointer arithmetic
  - Array walking with bad index value
- Java: cannot happen (will throw an exception)

Memory Read Out of Bounds

- A region of invalid memory is read instead of a valid one
- Impacts
  - Errors in computations
  - **Sensitive values could be read**
- Causes
  - Reading of a string not terminated by a null
  - Array walking with bad index
- Java: cannot happen (will throw an exception)

Resource Leak

- A no longer needed resource is not returned to the available pool
  - Memory, file handle, network connection, …
- Impacts
  - Depends on the resource and its usage
  - **Can lead to slowdown and crash**
- Causes
  - Reference lost because of pointer reuse
  - Programmer forgot to free the resource
- Java: the garbage collector helps a lot

Program Hang

- Program is in an infinite loop or wait state
- Impacts
  - Denial of service
- Causes
  - Threads in deadlock state
  - Conditions to exit a loop never reached

Program Crash

- An unrecoverable error happens and the execution of the program is stopped
- Impacts
  - Denial of service
- Causes
  - Dereference of an invalid pointer (page fault)
  - Uncaught exception
  - Division by zero

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Vulnerabilities

- Errors in general are undesirable
- But the real problem is vulnerabilities
  - Especially the remotely-exploitable ones
- A vulnerability allows an attacker to have some form of control over the program
  - Influence the flow of control
  - Influence the flow of data
- Memory read or written out of bounds
  - Cause of most dangerous vulnerabilities

Denial of Service

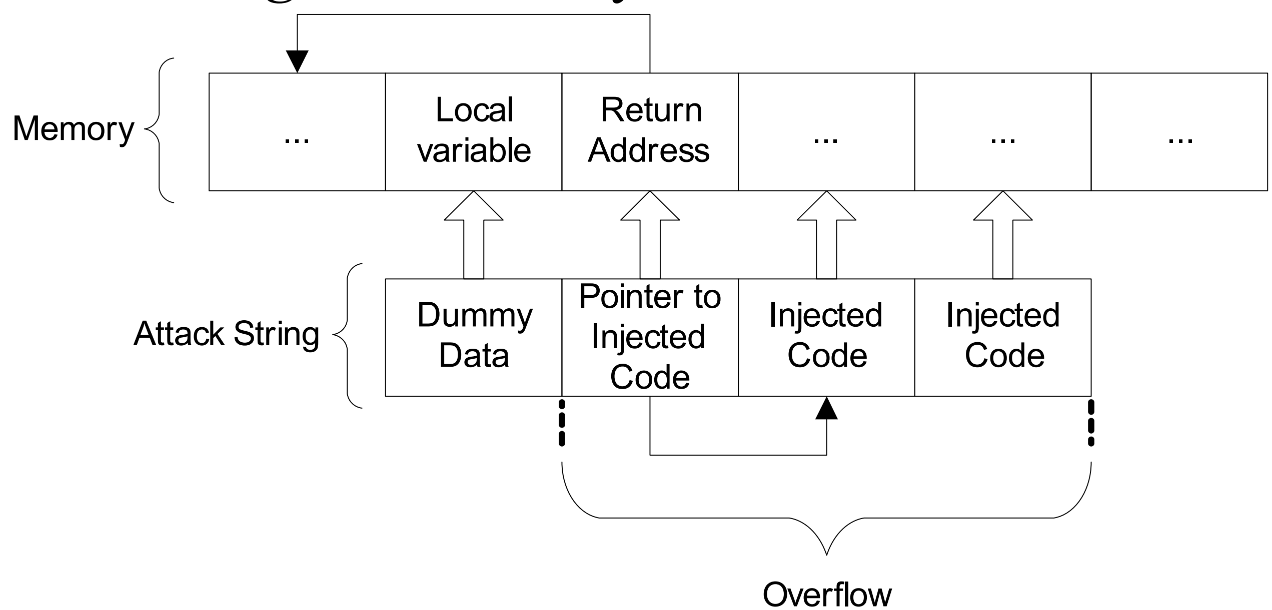
- Allows an attacker to prevent users from getting correct service
- How it's usually done
  - Create an unrecoverable error condition
  - Exploit a resource leak
- Java
  - Most program sanity problems throw unchecked exceptions
  - Problems are "transformed" into denials of service if exceptions are not caught

Unauthorized Access

- Allows an attacker to access functionalities without the required authorization
- How it's usually done
  - Bypass the control mechanism by modifying it in memory
  - Read sensitive values in memory and use them to get access

Code Injection

- Overwrite a function pointer that will be called
- Allows an attacker to take control of a process by redirecting its execution **to his own code**
- Also known as *buffer overflow* or *stack smashing* vulnerability



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Pitfalls & Shortcomings of C/C++

- Many errors are possible because of choices made when C/C++ were created
- These choices
  - Require too much "micro-management" of the program's behavior
  - "Encourage" mistakes
  - Give serious consequences to seemingly benign errors
- Java creators had these problems in mind and got rid of the majority of them

C/C++ Lack of Type-safety

- Type-safety ensures values assigned to variables are correct
  - Type-safety helps enforce the execution model
  - **Type-safe programs are *fail-fast***
- Execution of erratic programs is not stopped
  - Many *exploits* are using this fact
- Java programs are type-safe
  - Verified at compile time and load time

C/C++ Pointer Arithmetic

- The ability to change the value of a pointer without restriction
  - Can read or write anywhere in memory
  - Control mechanisms can be *bypassed*
  - Easy to create very obscure bugs
  - **Much higher verification complexity**
- There is no pointer arithmetic in Java

C/C++ Buffers Have a Static Size

- Buffers cannot grow to accommodate data
  - Buffer accesses are not checked
  - An overflow will overwrite memory
  - Validation is cumbersome
  - Source of *buffer overflow* vulnerabilities
- Java will throw an exception when an overflow occurs

C Lack of Robust String Type

- C has no type for character strings
  - Static buffers with overflow problems are used instead
  - Size of string indicated by a *null* at the end
  - Strings are used a lot in programs
  - Very fragile: what if the *null* is not there?
  - Source of *buffer overflow* vulnerabilities
- C++ programs can use the string type in the STL
  - Not used enough
- Java only has a robust string type

C/C++ Vulnerabilities in Std Libraries

- String manipulation functions
  - `strcpy()`, `gets()` and friends
  - Lack bounds checks for destination buffer
  - Possible overflow if data size is not checked
  - Source of *buffer overflow* vulnerabilities
  - Use replacement functions: `strncpy()`

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Defects: Some Observations

- Many defects are not ‘always on’
  - They will not always generate errors
  - Complex conditions have to be met
  - Input values play an important role
- Most defects are composite
  - Cannot be attributed to a single program instruction
  - A defect can be the absence of something
    - Data validation
- Mostly C/C++ defects – (selection of 25)

Defects

1 – Memory Management Faults

1.1 – Reading of freed memory

1.2 – Under allocated memory for a given type

1.3 – Call of `free()` with an invalid pointer

1.4 – Incorrect C++ array deletion

1.5 – Call of `memcpy()` with overlapping memory regions

1.6 – Reading of an uninitialized variable

1.7 – Non-virtual destructor of derived class not called

Defects

2 – Overrun and Underrun Faults

- 2.1 – Overrun or underrun of an array
- 2.2 – Dereference of a past-the-end C++ iterator
- 2.3 – Dereference of an erased C++ iterator
- 2.4 – Incorrect size parameter to a buffer function
- 2.5 – Use of negative array index or size
- 2.6 – Reading of a string of arbitrary length without limit
- 2.7 – Reading of a non null-terminated string

Defects

3 – Pointer Faults

- 3.1 – Return of a pointer to a local variable
- 3.2 – Incorrect pointer arithmetic
- 3.3 – Dereference of a null pointer
- 3.4 – Resource reference lost

4 – Incorrect Arithmetic Faults

- 4.1 – Division by zero
- 4.2 – Integer overflow or underflow
- 4.3 – Bit shift bigger than integral type or negative

Defects

5 – Cast Faults

- 5.1 – Integer sign lost because of implicit unsigned cast
- 5.2 – Integer precision lost because of bad cast

6 – Miscellaneous Faults

- 6.1 – Unspecified format string
- 6.2 – Endless loop

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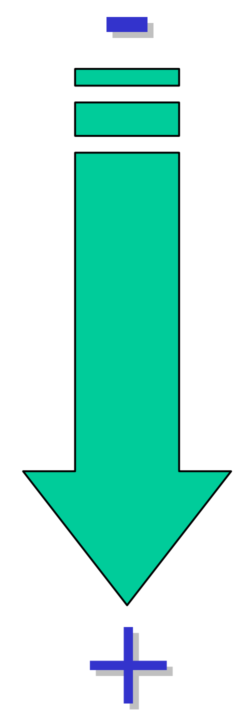
Tools Overview

- Evaluated tools – most are multiplatform
  - C/C++: 27 tools
  - Java: 37 tools
- Free (open source) versus commercial tools
  - C/C++: best tools are commercial
  - Java: many good free tools
- Most academic tools are only proofs of concepts
- Evaluation criteria
  - Precision, scalability, coverage, diagnostic

Tools

Required Investment*



1. Program Conformance Checkers
   - Detect defects
2. Runtime Testers
   - Detect errors
3. Advanced Static Analyzers
   - Detect defects

* In money, time, training, resources, etc.

Program Conformance Checkers

- Check source code for common *bug patterns*
- Lightweight analysis based on syntax
  - Excellent scalability
  - Many false positives and negatives
  - Poor performance except for a few defects
    - E.g.: unspecified format string
- Many free tools are in this category

Program Conformance Checkers

C/C++

- **Secure Programming Lint**
  - C only
  - Many "parse errors"
  - Superficial analysis without annotations
- **FlawFinder**
  - Format strings
  - Vulnerable functions
  - A lot of false positives

Java

- **PMD**
  - Enforces coding conventions
  - Well integrated
  - Cut & paste detector
- **AppPerfect CodeAnalyzer**
  - Similar to PMD
    - Different rules
  - Affordable & effective

Runtime Testers

- Program behavior cannot always be deduced statically
  - Some values are not known before runtime
- Look for errors while the program is running
  - Code is instrumented with checks
  - Fine-grained analysis
  - Excellent scalability
  - Coverage can be poor without a good strategy
- Excellent for composite defects related to memory usage

Runtime Testers

C/C++

- **Parasoft Insure++**
  - Source instrumentation
  - Impressive performance
  - Easy to use (debugger)
  - Good diagnostic
- **Rational Purifier**
  - Similar to Insure++
  - Analysis not as thorough

Java

- **AppPerfect Java Profiler**
  - Heap, threads, objects, CPU usage, disk I/O, memory usage
  - Heap browser
  - Deadlock detection
- **JProfiler**
- **NetBeans Profiler**

Advanced Static Analyzers

- Work on program semantics instead of syntax
  - Use formal methods, like abstract interpretation or model-checking
  - Scalability is often problematic
- Code must be compiled into a model
  - A lot of code portability issues
- Generally much slower than other tools
- Very sophisticated tools: often expensive

Advanced Static Analyzers

C/C++

- **Coverity Prevent (SWAT)**
  - Good integration with makefiles
  - Excellent diagnostic with execution trace
  - Surprisingly scalable
- **PolySpace for C++**
  - Very thorough but slow and memory hungry
  - Can detect runtime exceptions statically

Java

- **ESC/Java 2**
  - Can prove properties on the behavior of programs
  - Have to add annotations
  - Very powerful
  - Hard to use
  - A must-have for critical Java software development

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C/C++ Evaluation

- Preliminary tests showed only 3 tools could help us achieve our goal:
  - Coverity Prevent
  - Parasoft Insure++
  - PolySpace for C++
- 2 sets of tests
  - Synthetic tests for every kind of defect (25)
  - Buggy code in production (~10,000 lines)

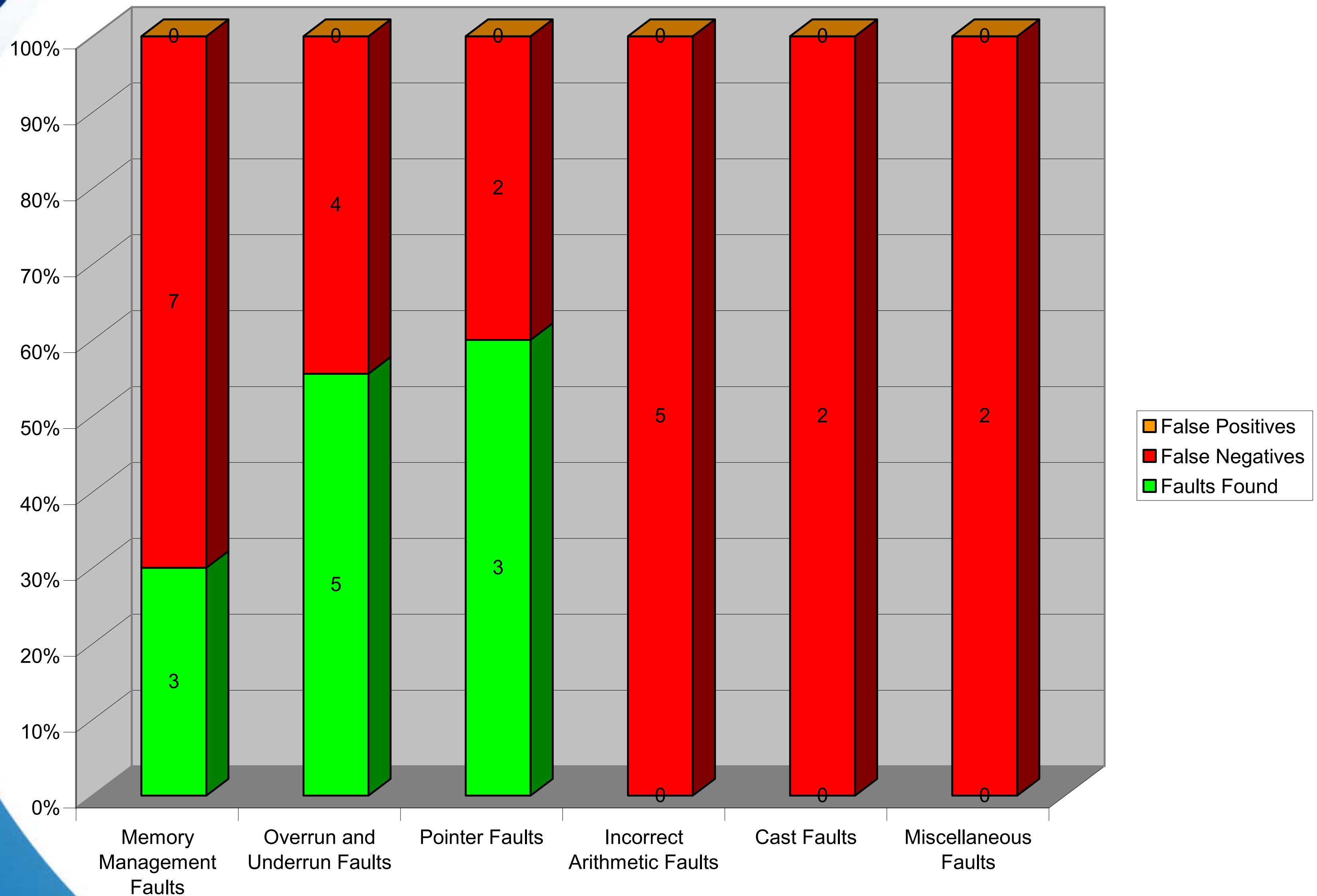
Comparing Apples and Oranges

- Error detection vs. defect detection
  - A conversion is necessary
- Synthetic tests
  - Defects are known
  - The errors they will cause too
  - Easy to convert everything to defects
- Buggy code in production
  - Defects are not known in advance
    - Used best result as baseline (errors)

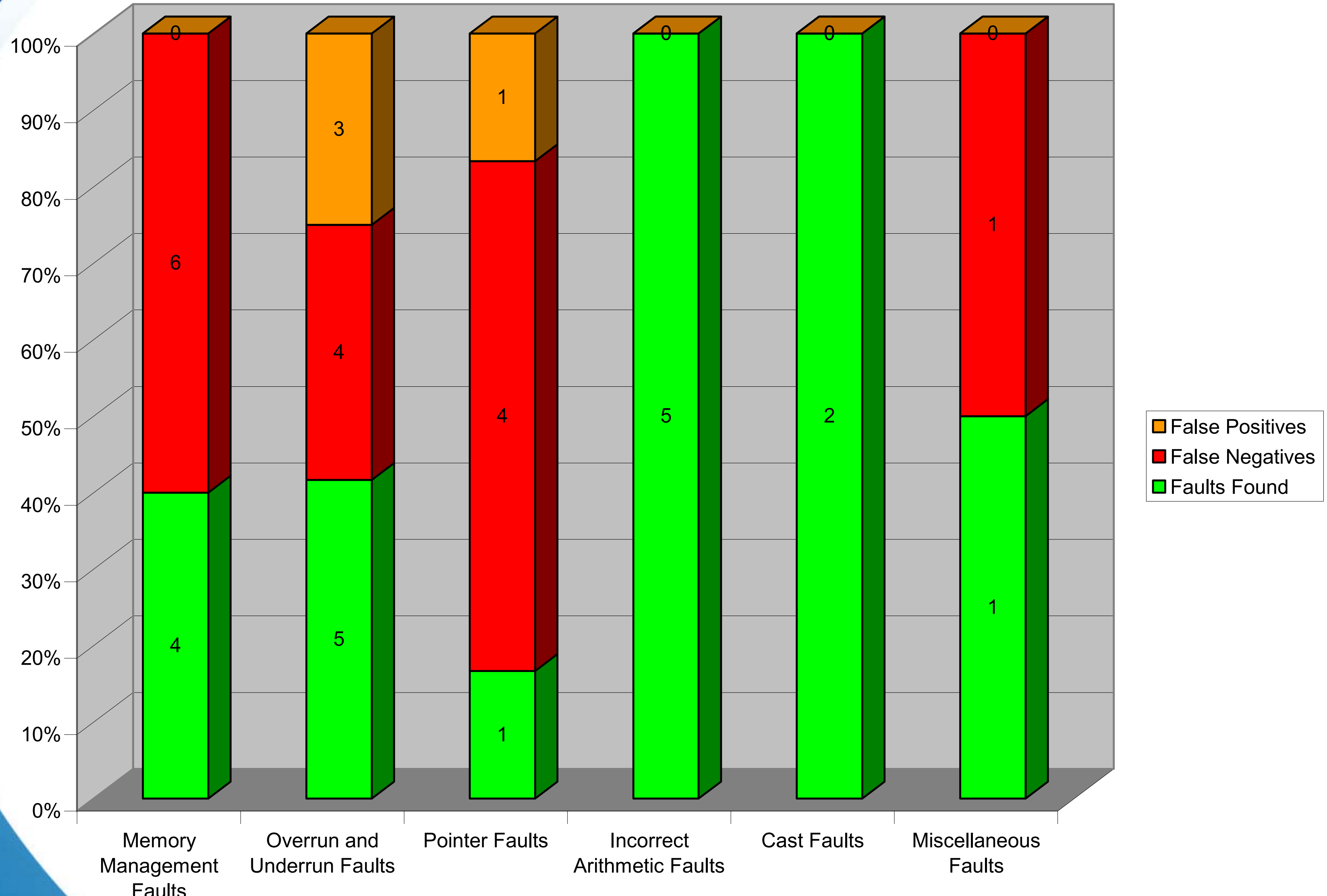
Results of Synthetic Tests

- A C++ class for every kind of defect (25)
- Integrated in a small high-quality open-source application (Windows MFC)
- Tests that would lead to a program crash or hang were deactivated for Insure++
- Tests are called from the `main()`
  - MFC applications have a “special” `main()`
  - PolySpace had to be used in a “class by class” analysis mode
- **No tool tries to detect every kind of defect or error**

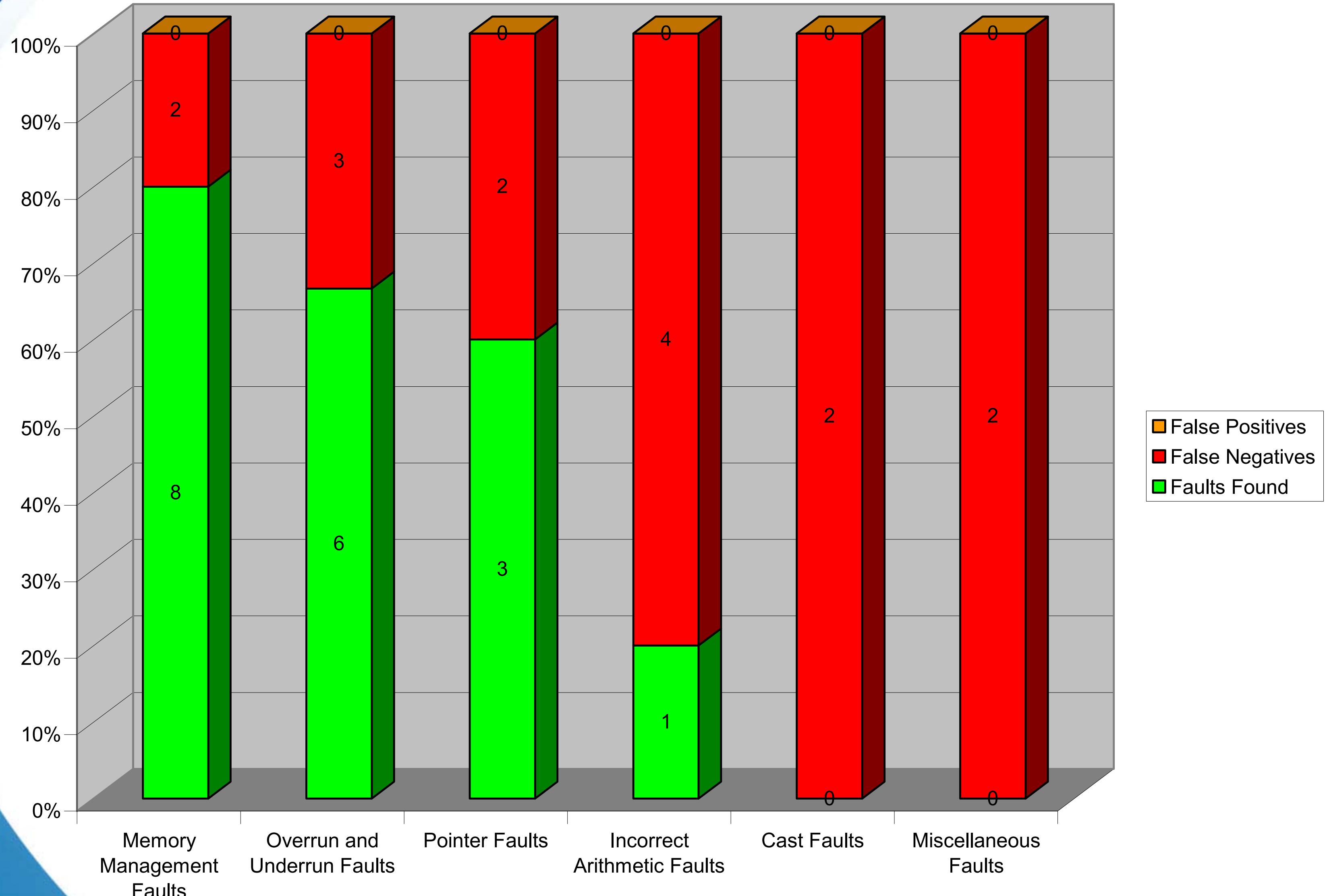
Results of Synthetic Tests - Coverity



Results of Synthetic Tests – PolySpace



Results of Synthetic Tests – Insure++



Results of Buggy Code in Production

- Numerical analysis application
  - About 10,000 lines of code
  - In production for many years
  - Reads a file and displays the results
    - Not a reactive program like MFC Apps
  - Bad quality code
    - "C+" design
    - A lot of cut and pasted, "spaghetti" code
    - **Really a worst-case scenario**

Results of Buggy Code in Production

Errors	Cov	Ins	Pol*
Memory write out of bounds	0	42	2
Memory read out of bounds	1	114	0
Resource leak	2	10	0
Program crash	2	0	0

* Over 300 false positives, ~16 hours of computation

C/C++ Analysis

- Static analysis tools need good quality code to perform well
  - Pointer arithmetic and void pointers can also be problematic
  - PolySpace will stop the analysis of a branch when a critical error is found
- Code portability issues
  - Preprocessor definitions and conditional compilation
  - Compiler-specific extensions to C/C++

Java Evaluation

- Preliminary tests showed 11 tools could be useful
- The ones that stand out:
  - AppPerfect DevSuite
  - PMD
- 2 large, open-source applications tested

Java Analysis

- Java design is better: less low-level defects
  - Fewer problems to look for
  - **Tools for Java are great to assess software quality**
- No code portability issues
  - A lot easier than C/C++

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Conclusion

- Security problems generally don’t come from the failure of security mechanisms
  - The failure occurs at a lower level
- C/C++ are especially problematic
  - Enforce almost no restriction on execution
  - Vulnerabilities with serious consequences
- Java is immune to most C/C++ problems
  - No serious vulnerabilities

Conclusion

- Best usage scenario for Coverity
  - Whole applications compiled with makefiles
- Best usage scenario for PolySpace
  - Small sections of critical code where runtime exceptions should never happen
- Best usage scenario for Insure++
  - Integrated to test cases
  - Test of hybrid systems based on many heterogeneous components
    - Values are always available at runtime

Conclusion

- Verifying C/C++ programs is a huge challenge
  - These languages are very hard to analyze
    - Undefined behaviors, pointers, compiler-specific extensions, etc.
  - No verification tool can reduce the risk significantly enough for this context
- For sensitive applications, we recommend the use of Java or any managed .Net language
  - Use C/C++ only if you really have to
    - Restricted language usage, test cases, and the use of verification tools are a must

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http://www.drdc-rddc.gc.ca/researchtech/malicots/home_e.asp

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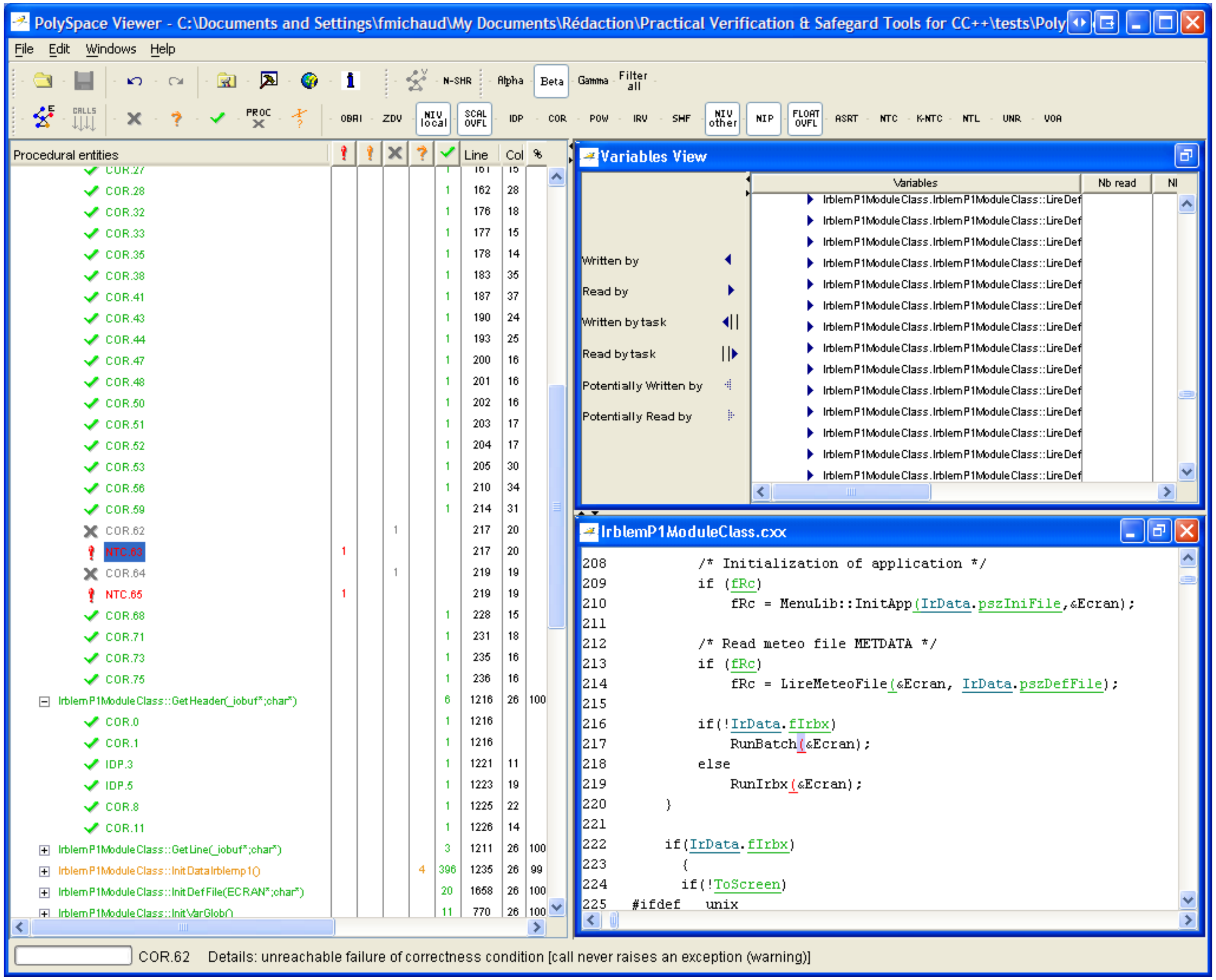
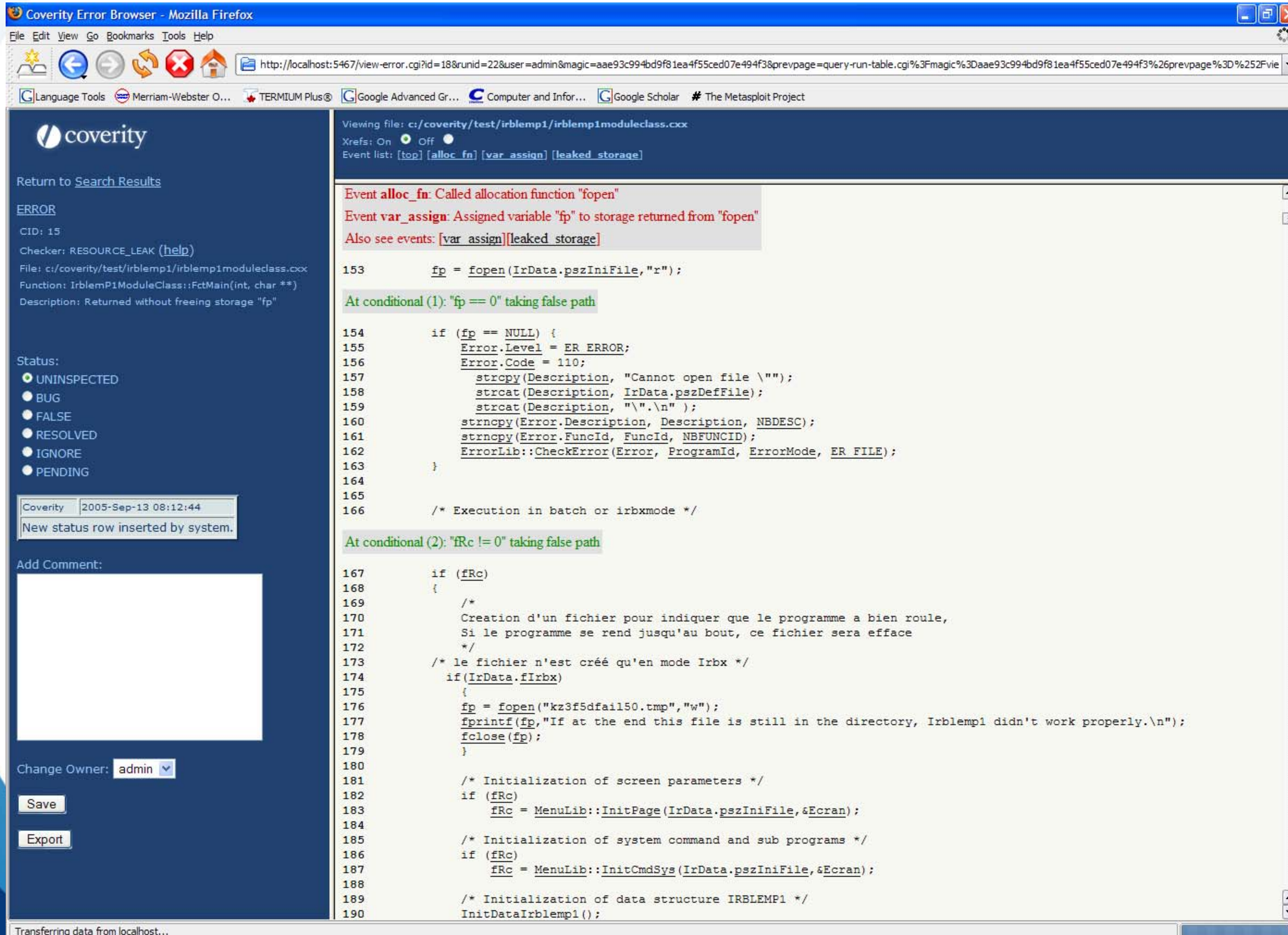
The Way Ahead

- Detection of higher level security problems
  - A model for the security behavior of programs is needed
- Automatic program hardening
  - Based on aspect oriented programming
- Current research project
  - Partnership with NSERC, Bell University Labs and Concordia University

PolySpace Viewer



Coverity Prevent



Insure

Insure - irblemp1_case2.txt - Notepad

File Edit Format View Help

```
[IrblemP1ModuleClass.cxx:843] **LEAK_ASSIGN**
>>                      IrData.pszDefFile = (char*) malloc(strlen(ppszParam[i+1])+1);

  Memory leaked due to pointer reassignment: IrData.pszDefFile

  Lost block : 0x01a81760 thru 0x01a8176a (11 bytes)
               IrData.pszDefFile, allocated at IrblemP1ModuleClass.cxx, 776
                          malloc()  (interface)
IrblemP1ModuleClass::InitVarGlob()  IrblemP1ModuleClass.cxx, 776
    IrblemP1ModuleClass::FctMain()  IrblemP1ModuleClass.cxx, 122
                    start_Module()  mainirblemp1.cpp, 435
                            main()  mainirblemp1.cpp, 447

  Stack trace where the error occurred:
  IrblemP1ModuleClass::ParsParam()  IrblemP1ModuleClass.cxx, 843
    IrblemP1ModuleClass::FctMain()  IrblemP1ModuleClass.cxx, 125
                    start_Module()  mainirblemp1.cpp, 435
                            main()  mainirblemp1.cpp, 447


[IrblemP1ModuleClass.cxx:7299] **READ_OVERFLOW**
>>                        *((int*)IrData.lstOptUpper.pElem[0].pDefData) = atoi(pszValue);

  String is not null terminated within range: <argument 1>

  Reading    : 0x0012f87c
  From block: 0x0012f87c thru 0x0012f97b (256 bytes)
             pszValue, declared at IrblemP1ModuleClass.cxx, 7225

  Stack trace where the error occurred:
                            atoi()  (interface)
IrblemP1ModuleClass::LireDefUpper()  IrblemP1ModuleClass.cxx, 7299
IrblemP1ModuleClass::InitDefFile()  IrblemP1ModuleClass.cxx, 1707
    IrblemP1ModuleClass::FctMain()  IrblemP1ModuleClass.cxx, 193
                    start_Module()  mainirblemp1.cpp, 435
                            main()  mainirblemp1.cpp, 447
```

AppPerfect DevSuite