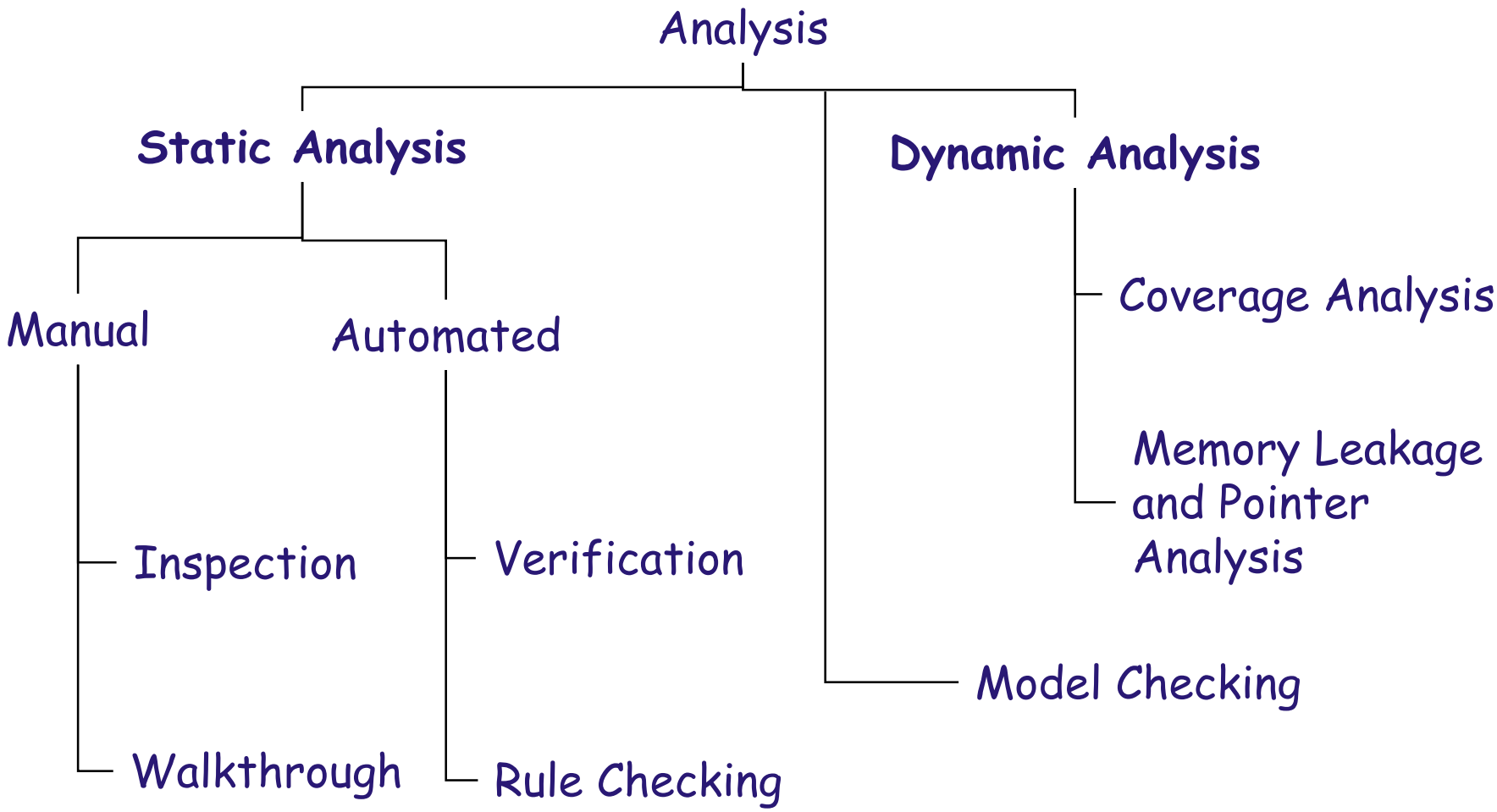
Analysis
Tools & Techniques

Taxonomy


Analysis
Static Analysis
Dynamic Analysis
Manual
Automated
Coverage Analysis
Memory Leakage and Pointer Analysis
Inspection
Verification
Model Checking
Walkthrough
Rule Checking

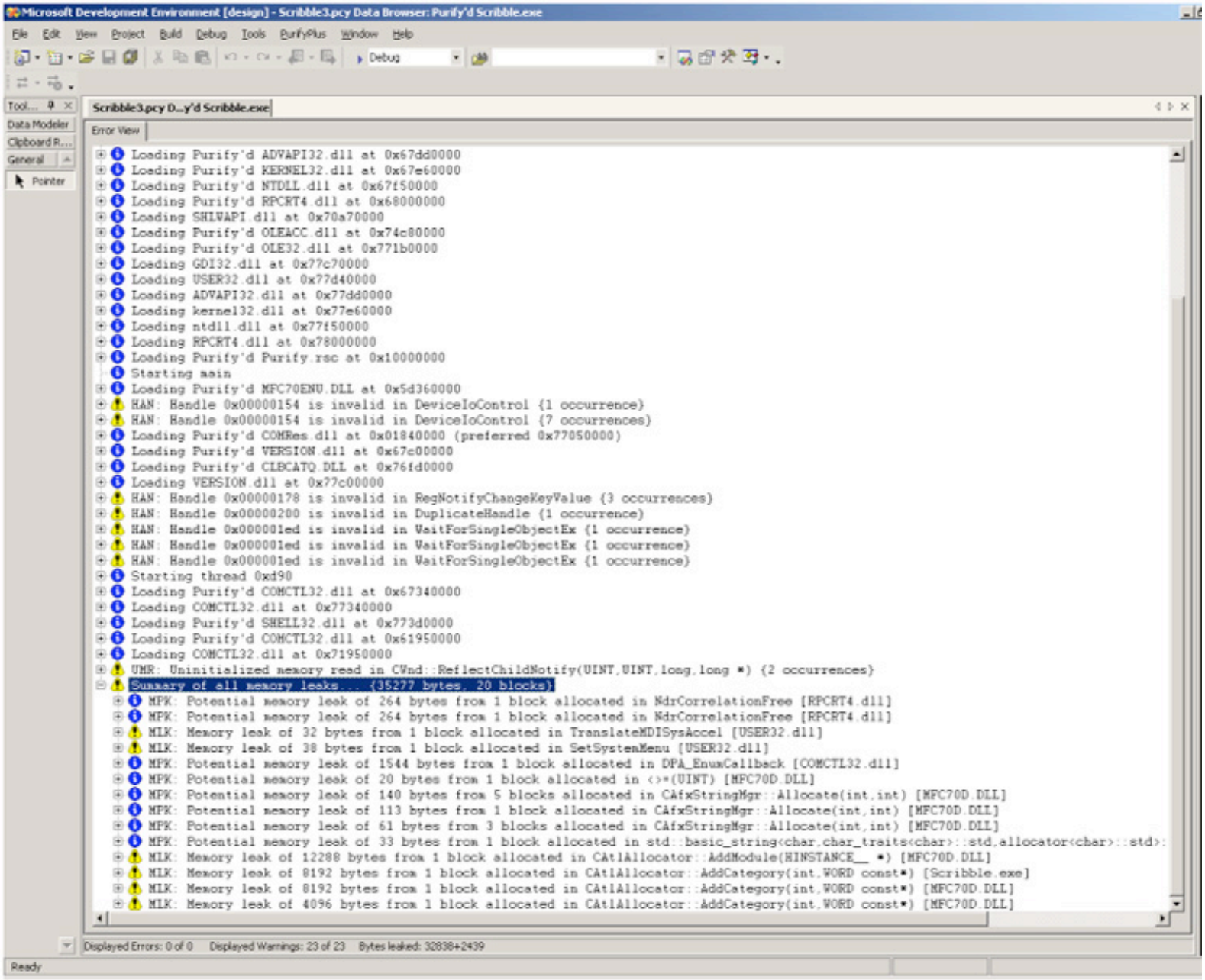
Dynamic Tools

- Purify (formerly Rational, now owned by IBM)
- Insure++ (Parasoft)
- Valgrind (free)
- Helgrind (free)
- Time Rover (Temporal Solutions)

Purify Features

- Errors Detected
  - array bounds errors
  - accesses through dangling pointer
  - uninitialized memory read
  - memory allocation errors
  - memory leaks
- Filtering and detail level customization
- GUI and command line interface
- Integrated with VC++, ClearQuest, TestFactory

Purify


Microsoft Development Environment [design] - Scribble3.pcy Data Browser: Purify'd Scribble.exe
File Edit View Project Build Debug Tools PurifyPlus Window Help
Debug
Scribble3.pcy D...y'd Scribble.exe
Error View
Loading Purify'd ADVAPI32.dll at 0x67dd0000
Loading Purify'd KERNEL32.dll at 0x67e60000
Loading Purify'd NTDLL.dll at 0x67f50000
Loading Purify'd RPCRT4.dll at 0x68000000
Loading SHLWAPI.dll at 0x70a70000
Loading Purify'd OLEACC.dll at 0x74c80000
Loading Purify'd OLE32.dll at 0x771b0000
Loading GDI32.dll at 0x77c70000
Loading USER32.dll at 0x77d40000
Loading ADVAPI32.dll at 0x77dd0000
Loading kernel32.dll at 0x77e60000
Loading ntdll.dll at 0x77f50000
Loading RPCRT4.dll at 0x78000000
Loading Purify'd Purify.rsc at 0x10000000
Starting main
Loading Purify'd MFC70ENU.DLL at 0x5d360000
HAN: Handle 0x00000154 is invalid in DeviceIoControl {1 occurrence}
HAN: Handle 0x00000154 is invalid in DeviceIoControl {7 occurrences}
Loading Purify'd COMRes.dll at 0x01840000 (preferred 0x77050000)
Loading Purify'd VERSION.dll at 0x67c00000
Loading Purify'd CLBCATQ.DLL at 0x76fd0000
Loading VERSION.dll at 0x77c00000
HAN: Handle 0x00000178 is invalid in RegNotifyChangeKeyValue {3 occurrences}
HAN: Handle 0x00000200 is invalid in DuplicateHandle {1 occurrence}
HAN: Handle 0x000001ed is invalid in WaitForSingleObjectEx {1 occurrence}
HAN: Handle 0x000001ed is invalid in WaitForSingleObjectEx {1 occurrence}
HAN: Handle 0x000001ed is invalid in WaitForSingleObjectEx {1 occurrence}
Starting thread 0xd90
Loading Purify'd COMCTL32.dll at 0x67340000
Loading COMCTL32.dll at 0x77340000
Loading Purify'd SHELL32.dll at 0x773d0000
Loading Purify'd COMCTL32.dll at 0x61950000
Loading COMCTL32.dll at 0x71950000
UMR: Uninitialized memory read in CWnd::ReflectChildNotify(UINT,UINT,long,long *) {2 occurrences}
Summary of all memory leaks... {35277 bytes, 20 blocks}
MPK: Potential memory leak of 264 bytes from 1 block allocated in NdrCorrelationFree [RPCRT4.dll]
MPK: Potential memory leak of 264 bytes from 1 block allocated in NdrCorrelationFree [RPCRT4.dll]
MLK: Memory leak of 32 bytes from 1 block allocated in TranslateMDISysAccel [USER32.dll]
MLK: Memory leak of 38 bytes from 1 block allocated in SetSystemMenu [USER32.dll]
MPK: Potential memory leak of 1544 bytes from 1 block allocated in DPA_EnumCallback [COMCTL32.dll]
MPK: Potential memory leak of 20 bytes from 1 block allocated in <>*(UINT) [MFC70D.DLL]
MPK: Potential memory leak of 140 bytes from 5 blocks allocated in CAfxStringMgr::Allocate(int,int) [MFC70D.DLL]
MPK: Potential memory leak of 113 bytes from 1 block allocated in CAfxStringMgr::Allocate(int,int) [MFC70D.DLL]
MPK: Potential memory leak of 61 bytes from 3 blocks allocated in CAfxStringMgr::Allocate(int,int) [MFC70D.DLL]
MPK: Potential memory leak of 33 bytes from 1 block allocated in std::basic_string<char,char_traits<char>::std,allocator<char>::std>:
MLK: Memory leak of 12288 bytes from 1 block allocated in CAtlAllocator::AddModule(HINSTANCE__ *) [MFC70D.DLL]
MLK: Memory leak of 8192 bytes from 1 block allocated in CAtlAllocator::AddCategory(int,WORD const*) [Scribble.exe]
MLK: Memory leak of 8192 bytes from 1 block allocated in CAtlAllocator::AddCategory(int,WORD const*) [MFC70D.DLL]
MLK: Memory leak of 4096 bytes from 1 block allocated in CAtlAllocator::AddCategory(int,WORD const*) [MFC70D.DLL]
Displayed Errors: 0 of 0
Displayed Warnings: 23 of 23
Bytes leaked: 32838+2439
Ready

Runtime Debugger Technology

- Two main techniques:
  - Object Code Insertion (used by Purify)
    - Instrumentation of the code happens on the executable file.
    - Involves the instrumentation of each object file and library by adding special instructions to every store and read instructions.
    - Allows analysis *even if you don't have the source code.*
  - Source Code Insertion
    - Instrumentation of the code happens on the source file
    - Involves parsing, analyzing and converting the original code into a new equivalent source code. Then Compile the new code.
    - Generally more accurate and has access to more information about the program pointers and memory blocks. Can detect errors at compile time also.

Array bounds errors

- **Purify reports Array Bounds Read and Array Bounds Write**
- Program writes memory past the bounds of an allocated block
- Memory corrupted may be used much later in the program
- Symptom far away from the cause
- Program may behave in an unpredictable way, dependent upon the values accessed in the memory block corrupted.

Accesses through dangling pointer

- **Purify reports Free Memory Read and Free Memory Write**
- Access to a freed block of memory
- Access can be a Read or a Write
- Outcome of program is unpredictable:
  - if memory block not reallocated, expected value might still be there, and program seems OK
  - if memory block reallocated program might fail, dependent on timing issues, memory allocation pattern,…

Uninitialized memory read

- **Purify reports Uninitialized Memory Read**
- Read to an allocated block of memory not yet initialized.
- Outcome of program is unpredictable, depending on the context.
- If memory contains value remaining from previous memory use, program will behave erratically

Memory allocation errors

- **Purify reports Freeing Mismatched Memory and Freeing Invalid Memory**
- Memory allocated with **new** but freed with **free** (instead of **delete**) may cause corruption of heap structures.
- If these structures are accessed, program can fail.
- Attempt to free a local variable on the stack might succeed and corrupt local variables or function return.

Memory leaks

- **Purify reports Memory Leaks**
- Memory allocated but **never freed**, and for which no pointers exist.
- Memory blocks cannot be used nor freed, and occupy address space.
- Performance of the program degrades and eventually it fails from lack of memory

Purify Shortcomings

- Purify does not detect corruption on the **stack** or in **static memory** at all, only for dynamic memory.

Electric Fence (Linux)

- Allocate arrays in separate virtual memory segments.
- Use memory management *hardware* checking to detect out-of-bounds references.

Insure++
(Parasoft)

- Software solution, source-level
- Checks all types of memory references including those to static (global), stack, and shared memory.
- Can find memory corruption and memory leaks as well as errors allocating and freeing dynamic memory.
- Automatically finds (some of) these kinds of errors:
  - string manipulation errors,
  - operations on uninitialized pointers,
  - operations on pointers to unrelated data blocks,
  - invalid pointer operations,
  - incompatible variable declarations,
  - mismatched variable types.

Insure++ Mutation Testing

- Leverages techniques from traditional Mutation Testing to uncover ambiguities that are difficult to detect through other methods or tools.
- Whereas traditional Mutation Testing attempts to create "faulty" mutants to create a more effective test suite, Insure++ creates and executes what should be **functionally equivalent mutants** of the source code under test.
- When one of these mutants performs differently than the original program, it **indicates that the code's functionality relies on implicit assumptions which may not always be satisfied during execution**.
- If a mutant causes the program to crash or encounter other serious problems, it's a sign that when the assumptions are not satisfied, serious errors will occur at runtime.

Insure++ Mutation Testing

- Because Mutation Testing can uncover a number of otherwise hard-to-find or esoteric errors, it is particularly important in C++, where there are so many opportunities to make errors.

- For example, Mutation Testing can detect errors such as lack of copy constructors or bad copy constructors, missing or incorrect constructors, wrong order of initialization of code, problems with operations of pointers, and dependence on undefined behavior such as order of evaluation.

Valgrind
(http://valgrind.org/)

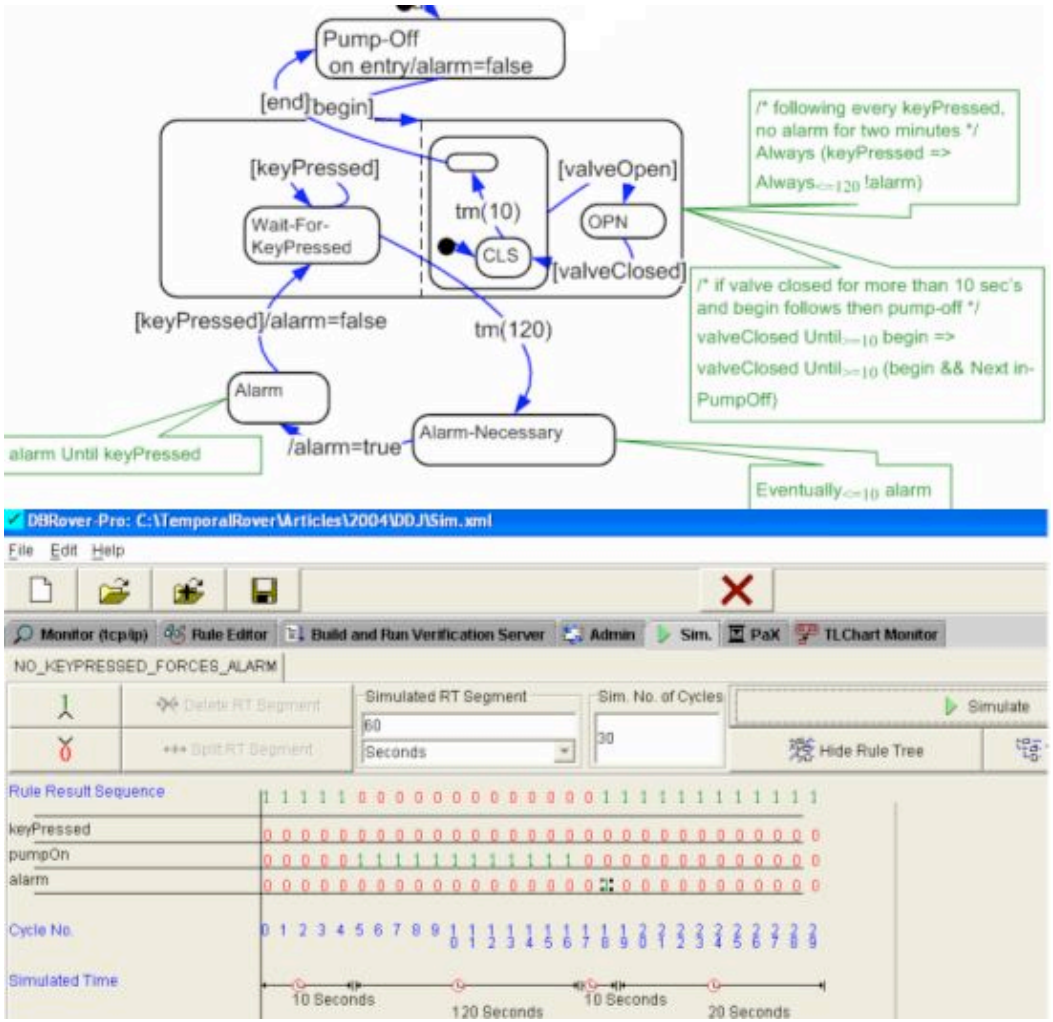
- **Valgrind Memcheck** detects memory-management problems, and is aimed primarily at C and C++ programs.
- When a program is run under Memcheck's supervision, all reads and writes of memory are checked, and calls to malloc/new/free/delete are intercepted.
- As a result, Memcheck can detect:
  - Use of uninitialized memory
  - Reading/writing memory after it has been free'd
  - Reading/writing off the end of malloc'd blocks
  - Reading/writing inappropriate areas on the stack
  - Memory leaks -- where pointers to malloc'd blocks are lost forever
  - Passing of uninitialized and/or unaddressable memory to system calls
  - Mismatched use of malloc/new/new [] vs free/delete/delete []
  - Overlapping src and dst pointers in memcpy() and related functions
  - Some misuses of the POSIX pthreads API

Helgrind: Race Detector

- Now part of Valgrind suite.
- Identifies **locations that are accessed by more than one thread**.
- For each such location, records which of the program's (pthread_mutex_) locks were held by the accessing thread at the time of the access.
- Checks whether there is indeed at least one lock which is used by all threads to protect that location.
- **If no such lock can be found**, then there is (apparently) no consistent locking strategy being applied for that location, and so a possible data race might result.
- Helgrind also allows for "thread segment lifetimes". If the execution of two threads cannot overlap -- for example, if your main thread waits on another thread with a pthread_join() operation -- they can both access the same variable without holding a lock.

Time Rover

Real-time monitoring based on temporal-logic assertions in State Charts



Examples of Temporal Logic Assertions

- ev1 and ev2 happen or do not happen simultaneously:
  Always ({ ev1 } Iff { ev2 })

- if ev1 then ev2 two cycles later:
  Always ({ ev1 } Implies (2){ ev2 })

- ev2 not before ev1:
  Always (Not{ev2} Until {ev1})

- ev2 any number of cycles after ev1:
  Always ({ev1} Implies Eventually {ev2})

Static Tools

- Polyspace (Patrick Cousot, now part of The MathWorks)
- Coverity Prevent (Dawson Engler)
- Klocwork
- CodeSurfer (GrammaTech)
- LintPlus (Cleanspace)
- PREfix/PREfast
- SLAM
- ESP

Polyspace Errors Detected

- Non-initialized variable read attempt
- Access conflicts for unprotected shared data in multi threaded applications
- Referencing through null pointers
- Out-of-bounds array access
- Out-of-bounds pointers
- Illegal type conversion
- Invalid arithmetic operations
- Overflow / underflow Unreachable code
- Invalid dynamic casts calls
- Throws of unauthorized exceptions
- Negative size arrays
- Null receivers
- Null pointers to members
- Wrong type for receivers
- Throws during catch parameter construction

Polyspace Analysis Output

Green	The code is safe - no run-time error. *You can focus your efforts elsewhere.*
Red	A run-time error will occur every time the operation is executed. *A solution should be implemented.*
Grey	The code is unreachable. *May point to an unimplemented functionality of the program.*
Orange	Warning - a run-time error *may* happen depending on the circumstances encountered at run-time. *Often missed by other methods, these errors can nonetheless cause major issues.*

Procedural entities	!	✗	?	✓	Line	Col	Details
Demo_Cpp	2	10	24	219			
__polyspace__edgstubs					1		__polyspace__edgst...
canalogic	1	3	2	11	1		canalogic.cpp
CAnalogic::TypeInfo()	1	3	2	11	12	15	canalogic.cpp
✓ COR.0				1	12		function never raises...
✓ COR.1				1	12		function returns a val...
✓ COR.2				1	14	12	call never raises an e...
✓ COR.3				1	15	18	call never raises an e...
✓ ASRT.4				1	17	2	failure of user asserti...
✓ ASRT.5				1	18	2	failure of user asserti...
✓ COR.6				1	20	10	call never raises an e...
✓ COR.7				1	23	18	call never raises an e...
✓ COR.8				1	23	18	non null receiver
✗ COR.10		1			24	4	correct type for recei...
✗ COR.9		1			24	4	correct type for recei...
✗ IDP.11		1			24	29	pointer within bounds
! COR.13	1				24	29	correct typeid argum...
✓ COR.16				1	26	18	call never raises an e...
✓ COR.17				1	26	18	non null receiver
? COR.18			1		29	2	correct type for recei...
? COR.19			1		29	2	correct type for recei...

Polyspace Source Highlighting

```
1
2     #include <cassert>
3     #include <typeinfo>
4
5     #include "canalogic.h"
6     #include "zz_utils.h"
7
8
9     static Utils  u;
10
11
12    int CAnalogic::TypeInfo()
13    {
14      CAnalogic canal;
15      const CAnalogic logic;
16
17      assert(typeid(logic) == typeid(canal));
18      assert(typeid(Capteur) == typeid(const Capteur));
19
20      Capteur cap;
21      Capteur* ptr = 0;
22
23      if (u.random_int())
24        return (typeid(this) ==  typeid (*ptr));
25
26      if (u.random_int())
27        ptr = &cap;
28
29      return 0;
30    }
31
32
33    // end
```

Coverity

- Seeded by research from Stanford professor Dawson Engler, et al.

- Target: "Commercial code typically has anywhere from **one to seven bugs per 1,000 LOC**, according to an April report from the National Cybersecurity Partnership's Working Group on the Software Lifecycle, which cited an analysis of development methods by the Software Engineering Institute at Carnegie Mellon University."

Coverity analyses

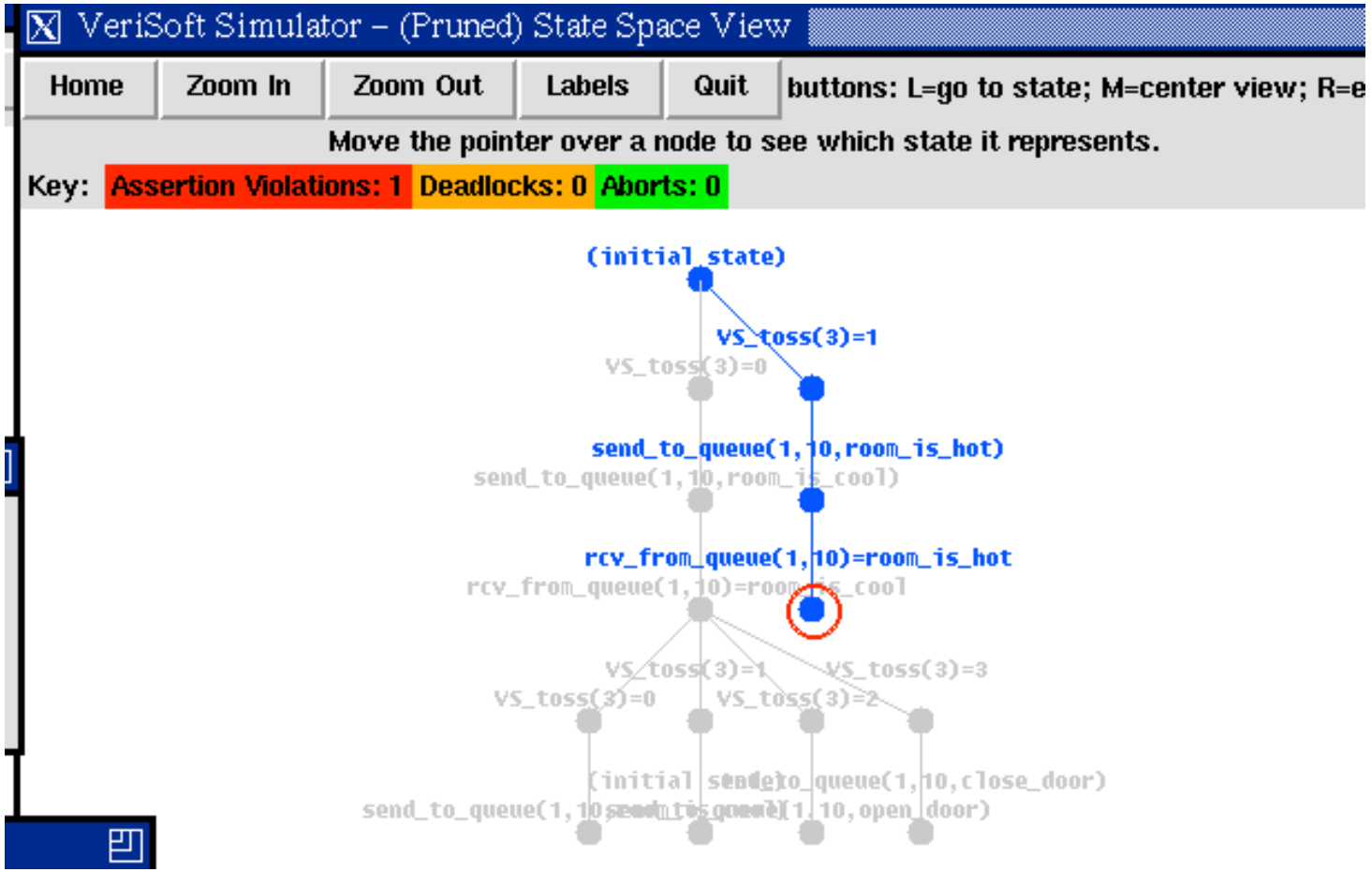
- MySQL: found an average of one bug in every 4,000 LOC --results that are at least four times better than is typical with commercial software.
- Linux kernel: found average of less than one flaw in every 10,000 LOC.

Model Checkers

- Generic model checking
  - Murphi
  - Spin/Promela (Gerard Holzmann, Bell Labs, JPL)
  - SMV
- Automatic model generation model checking
  - Verisoft
  - Pathfinder
  - Bandera
  - SLAM (sort of)

- UPAAL (Upsala University)
- SGM (State Graph Manipulation, Pao-Ann Hsiung)
- ASTRÉE

VeriSoft: Concurrent/Real-time



http://cm.bell-labs.com/who/god/verisoft/demo.html

VeriSoft Error Detection

- ***deadlocks***: a deadlock is a state of the state space where all processes are blocked.
- ***divergences***: a divergence occurs when a process does not attempt to communicate with the rest of the system for more than a given (user-specified) amount of time.
- ***livelocks***: a "livelock" occurs when a process is blocked during a sequence of more than a given (user-specified) number of successive states in the state space.
- ***assertion violations***: VS_assert operation can be inserted in the code of any process.

Excerpt from Case Study slides of Dawson Engler, founder of Coverity

We found bugs with static analysis and model checking and this is what we learned.

Dawson Engler and Madanlan Musuvathi
Based on work with
Andy Chou, David {Lie, Park, Dill}
Stanford University

What's this all about

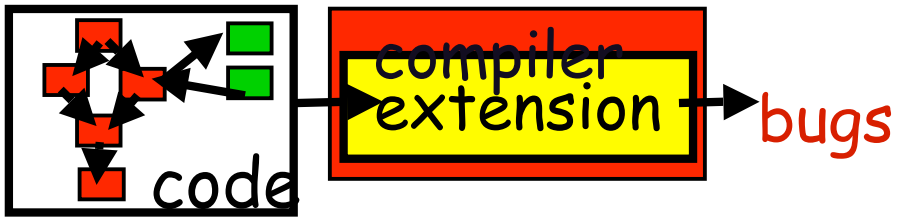
- A general goal of humanity: automatically find bugs
  - Success: lots of bugs, lots of code checked.

- Two promising approaches
  - Static analysis
  - Model checking
  - We used static analysis heavily for a few years & model checking for several projects over two years.

- General perception:
  - Static analysis: easy to apply but shallow bugs
  - Model checking: harder, but strictly better once done
  - Reality is a bit more subtle.

Crude definitions.

- "Static analysis" = our approach [DSL'97,OSDI'00]
  - Flow-sensitive, inter-procedural, extensible analysis
  - Goal: max bugs, min false pos
  - Not sound. No annotations.
  - Works well: 1000s of bugs in Linux, BSD, company code



- "Model checker" = explicit state space model checker
  - Use Murphi for FLASH, then home-grown for rest.
  - Limited domain: applying model checking to implementation code.

Cases

- Case 1: FLASH cache coherence protocol code
  - Checked w/ static analysis [ASPLOS'00]
  - Then w/ model checking [ISCA'01]
  - Surprise: static analysis found 4x more bugs.

- Case 2: AODV loop free, ad-hoc routing protocol
  - Checked w/ model checking [OSDI'02]
  - Took 3+ weeks; found ~ 1 bug / 300 lines of code
  - Checked w/ static (2 hours): more bugs when overlap

- Case 3: Linux TCP
  - Model checking: 6 months, 4 "ok" bugs.
  - Surprise: So hard to rip TCP out of Linux that it was easier to jam Linux into model checker

Some caveats

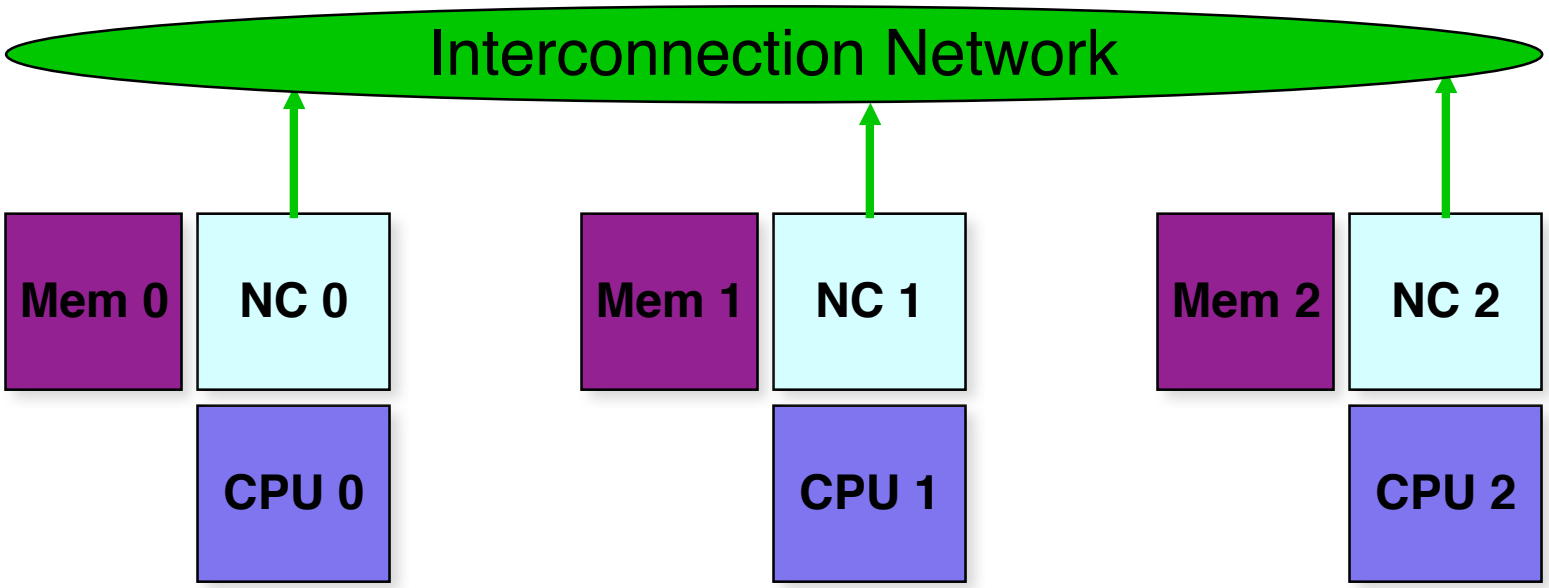
- Main bias:
  - Static analysis guy that happens to do model checking.
  - Some things that surprise me will be obvious to you.

  - We want model checking to succeed.
  - We're going to write a bunch more papers on it.
  - Life has just not always been exactly as expected.

- Of course
  - This is just a bunch of personal case studies
  - started up with engineers induction
  - to look like general principles. (1,2,3=QED)
  - While coefficients may change, general trends should hold

Case Study: FLASH

- ccNUMA with cache coherence protocols in software.
  - Has to be extremely fast
  - BUT: 1 bug deadlocks/livelocks entire machine
  - Heavily tested for 5 years.
  - Low-level with long code paths (73-183 LOC average)

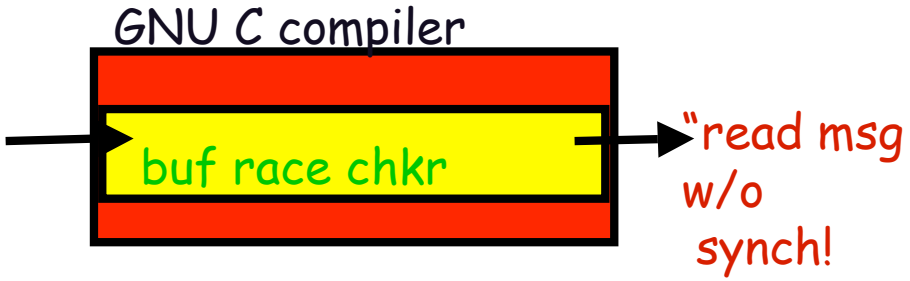


Finding FLASH bugs with static analysis

- Gross code with many ad hoc correctness rules
  - But: they have a clear mapping to source code.
  - Easy to check with compiler.
- Example:
  - WAIT_FOR_DB_FULL must precede MISCBUS_READ_DB

```
Handler:
  if(...)
    WAIT_FOR_DB_FULL();

  MISCBUS_READ_DB();
```



  - Nice: scales, precise, statically found 34 bugs