Software Excellence via Program Analysis at Microsoft

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Analysis of Software Artifacts
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Talking the talk …

- Program analysis technology can make a huge impact on how software is engineered
- The trick is to properly balance research on new techniques with a focus on deployment
- The Center for Software Excellence (CSE) at Microsoft is doing this (well?) today

… walking the walk

- Program Analysis group in June 2005
  - Filed 7000+ bugs
  - Automatically added 10,000+ specifications
  - Answered hundreds of emails

  (one future version of one product)
- We are program analysis researchers
  - but we live and breathe deployment & adoption
  - and we feel the pain of the customer

Context

- The Nail (Windows)
  - Manual processes do not scale to “real” software
- The Hammer (Program Analysis)
  - Automated methods for “searching” programs
- The Carpenter (CSE)
  - A systematic, heavily automated, approach to improving the “quality” of software

What is program analysis?

- grep == program analysis
- program analysis == grep

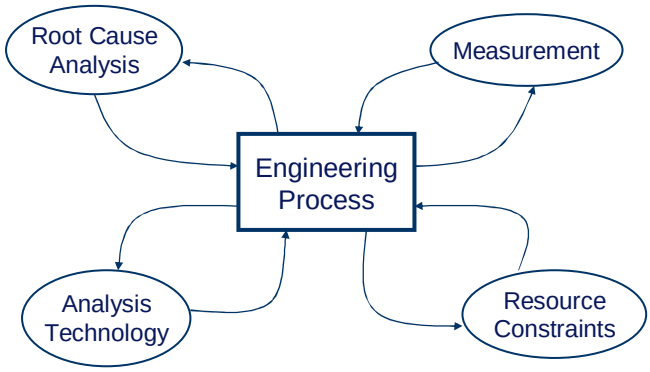
- syntax trees, CFGs, instrumentation, alias analysis, dataflow analysis, dependency analysis, binary analysis, automated debugging, fault isolation, testing, symbolic evaluation, model checking, specifications, …

Roadmap

- (part of) The engineering process today
- (some of) The tools that enable the process
- (a few) Program analyses behind the tools
- (too many) Lessons learned along the way
- (too few) Suggestions for future research

Engineering process

Methodology



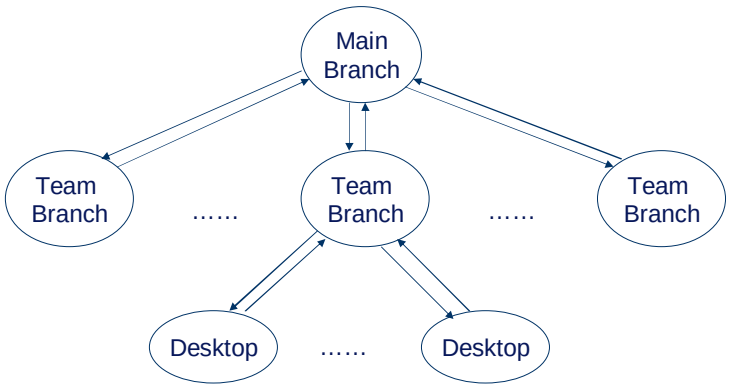
Root cause analysis

- Understand important failures in a deep way
  - Every MSRC bulletin
  - Beta release feedback
  - Watson crash reports
  - Self host
  - Bug databases
- Design and adjust the engineering process to ensure that these failures are prevented

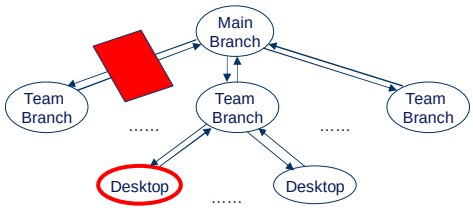
Measurement

- Measure everything about the process
  - Code quality
  - Code velocity
  - Tools effectiveness
  - Developer productivity
- Tweak the process accordingly

Process – Build Architecture

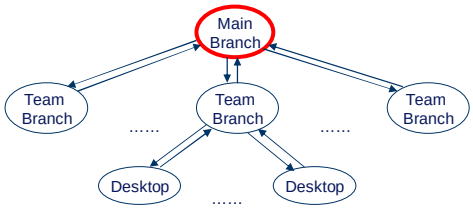


Process – Quality Gates



- Lightweight tools
  - run on developer desktop & team level branches
  - issues tracked within the program artifacts
- Enforced by rejection at gate

Process – Automated Bug Filing



- Heavyweight tools
  - run on main branch
  - issues tracked through a central bug database
- Enforced by bug cap

Tools

QG – Code Coverage via Testing

- Reject code that is not adequately tested
  - Maintain a minimum bar for code coverage
- Code coverage tool – Magellan
- Based on binary analysis - Vulcan

Magellan

- BBCover
  - low overhead instrumentation & collection
  - down to basic block level
- Sleuth
  - coverage visualization, reporting & analysis
- Blender
  - coverage migration
- Scout
  - test prioritization

QG – Component Integrity

- Reject code that breaks the componentized architecture of the product
  - Control all dependencies across components
- Dependency analysis tool – MaX
- Based on binary analysis - Vulcan

MaX

- Constructs a graph of dependencies between binaries (DLLs) in the system
  - Obvious : call graph
  - Subtle : registry, RPC, …
- Compare policy graph and actual graph
- Some discrepancies are treated as errors

Vulcan

- Input – binary code
- Output – program abstractions

- Adapts to level of debug information
- Makes code instrumentation easy
  - think ATOM
- Makes code modification easy
  - link time, post link time, install time, run time

QG – Formal Specifications

- Reject code with poorly designed and/or insufficiently specified interfaces

- Lightweight specification language – SAL
  - initial focus on memory usage
- All functions must be SAL annotated
- Fully supported in Visual Studio (see MSDN)

SAL

- A language of contracts between functions
- preconditions
  - Statements that hold at entry to the callee
  - What does a callee expect from its callers?
- postconditions
  - Statements that hold at exit from the callee
  - What does a callee promise its callers?
- Usage example:

  a_0 `RT func(`a_1 … a_n `T par)`
- Buffer sizes, null pointers, memory usage, …

SAL Example

- wcsncpy
  - precondition: destination must have enough allocated space

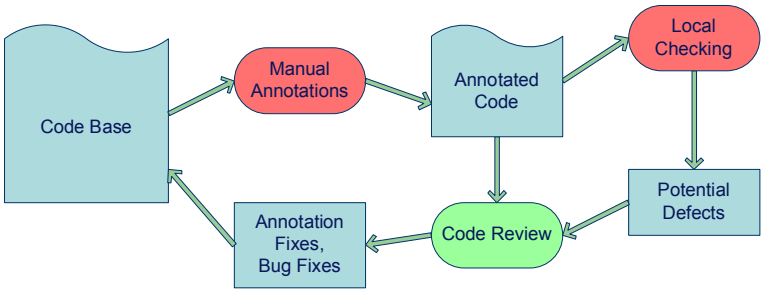
```
wchar_t wcsncpy (
 wchar_t *dest, wchar_t *src, size_t num );

wchar_t wcsncpy (
 __pre __writableTo(elementCount(num)) wchar_t *dest,
 wchar_t *src, size_t num );
```

SAL Principle

- Control the power of the specifications:
  - Impractical solution: Rewrite code in a different language that is amenable to automated analysis
  - Practical solution: Formalize invariants that are implicit in the code in intuitive notations
    - These invariants often already appear in comments

Defect Detection Process – 1



QG – Integer Overflow

- Reject code with potential security holes due to unchecked integer arithmetic
- Range specifications + range checker – IO
- Local (intra-procedural) analysis
- Runs on developer desktop as part of regular compilation process

IO

- Enforces correct arithmetic for allocations

```
size1 = …
size2 = …
data = MyAlloc(size1+size2);
for (i = 0; i < size1; i++)
  data[i] = …
```

- Construct an expression tree for every interesting expression in the code
- Ensure that every node in the tree is checked

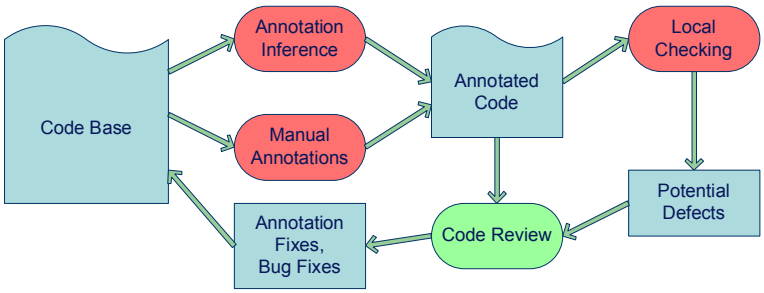
QG – Buffer Overruns

- Reject code with potential security holes due to out of bounds buffer accesses
- Buffer size specifications + buffer overrun checker – espX
- Local (intra-procedural) analysis
- Runs on developer desktop as part of regular compilation process

Bootstrap the process

- Combine global and local analysis:
  - Weak global analysis to infer (potentially inaccurate) interface annotations - SALinfer
  - Strong local analysis to identify incorrect code and/or annotations - espX

Defect Detection Process - 2



SALinfer

```
void work()
{
    int elements[200];
    wrap(elements, 200);
}

void wrap(pre elementCount(len) int *buf,
          int len)
{
    int *buf2 = buf;
    int len2 = len;
    zero(buf2, len2);
}

void zero(pre elementCount(len) int *buf,
          int len)
{
    int i;
    for(i = 0; i <= len; i++)
        buf[i] = 0;
}
```

Track flow of values through the code

1. Finds stack buffer
2. Adds annotation
3. Finds assignments
4. Adds annotation

espX

```
void work()
{
    int elements[200];
    wrap(elements, 200);
}

void wrap(pre elementCount(len) int *buf,
          int len)
{
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    zero(buf2, len2);
}

void zero(pre elementCount(len) int *buf,
          int len)
{
    int i;
    for(i = 0; i <= len; i++)
        buf[i] = 0;
}
```

Building and solving constraints

1. Builds constraints
2. Verifies contract
3. Builds constraints
   len = length(buf); i ≤ len
4. Finds overrun
   i < length(buf) ? NO!

QG – Code Correctness

- Reject code with potential crashes due to improper usage of memory
- Pointer usage specifications + memory usage checker – PREfast
- Managed code – PREsharp
- Local (intra-procedural) analysis
- Runs on developer desktop as part of regular compilation process

ABF – Code Correctness

- Tease out hard to find inter-component bugs that lead to crashes
  - null dereference, un-initialized memory, leaks, …
  - difficult to find accurately on the desktop
- Inter-procedural symbolic evaluation - PREfix

PREfix

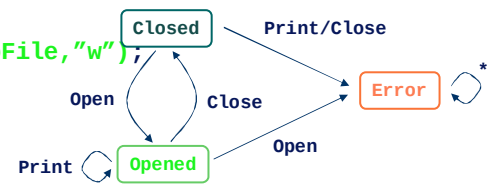
- Bottom-up process on the call graph
- Symbolic evaluation of a fixed number of distinct paths through each function
  - use symbolic state to remove infeasible paths
  - report defects
  - build function models for use by callers
- Solved all the difficult engineering problems for the inter-procedural tools to follow

ABF – Security

- For every new security issue, map it to a coding defect and root out all other instances
  - Each coding defect is a different pattern, but most can be viewed as finite state properties
- Heavyweight, thorough, property-based inter-procedural analysis - ESP

Property-based analysis

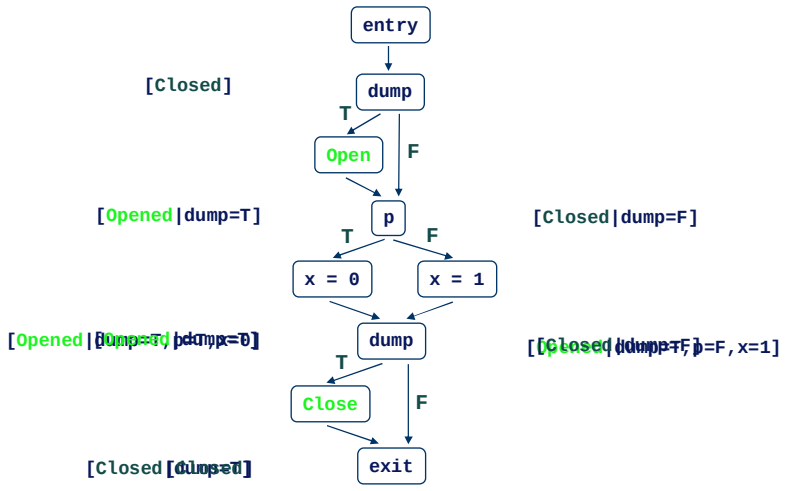
```
void main ()
{
  if (dump)
    Open: fopen(dumpFile,"w");

  if (p)
    x = 0;
  else
    x = 1;

  if (dump)
    Close: fclose(fil);
}
```



ESP

- Symbolically evaluate the program
  - track FSA state and execution state
- At control flow branch points:
  - Execution state implies branch direction?
    - Yes: process appropriate branch
    - No: split state and process both branches
- At control flow merge points:
  - States agree on property FSA state?
    - **Yes: merge states**
    - **No: process states separately**

Example



Lessons

Forcing functions for change

- Gen 1: Manual Review
  - Too many paths
- Gen 2: Massive Testing
  - Inefficient detection of common patterns
- Gen 3: Global Program Analysis
  - Stale results
- Gen 4: Local Program Analysis
  - Lack of context
- Gen 5: Specifications

Don’t bother doing this without -

- No-brainer must-haves
  - Defect viewer, docs, champions, partners
- A mechanism for developers to teach the tool
  - Suppression, assertion, assumption
- A willingness to support the tool
- A positive attitude

Myth 1 – Soundness matters

Sound == find only real bugs

- The real measure is Fix Rate
- Centralized: >50%
- Desktop: >75%
- Specification inference
  - Is it much worse than manual insertion?

Myth 2 – Completeness matters

Complete == find all the bugs

- There will never be a complete analysis
  - Partial specifications
  - Missing code
- Developers want *consistent* analysis
  - Tools should be stable w.r.t. minor code changes
  - Systematic, thorough, tunable program analysis

Myth 3 – Developers only fix real bugs

- Key attributes of a “fixable” bug
  - Easy to fix
  - Easy to verify
  - Unlikely to introduce a regression
- Simple tools can be very effective

Myth 4 – Developers hate specifications

- Control the power of the specifications
- This will work
  - Formalize invariants that are implicit in the code
- This will not work
  - Re-write code in a different language that is amenable to automated analysis
- Think like a developer

Myth 5 – Whiteboards are useful

- Whiteboards have held back defect detection
- The most useful analyses and tools mimic the thinking of the developer
  - e.g. do developers consider every possible interleaving when writing threaded code? No!

Myth 6 – Theory is useless

- Fundamental ideas have been crucial
  - Hoare logic
  - Abstract interpretation
  - Context-sensitive analysis with summaries
  - Alias analysis

Don’t break the shipping code ☺

- __invariant() is an annotation macro
  - generates code in the tools build, noop in the real build
- Before:

```
b = a + 16; Use(b);
```

- After (correct code):

```
__invariant(a); b = a + 16; Use(b);
```

- After (incorrect code):

```
b = __invariant(a) + 16; Use(b);
```

- Incorrect usage silently breaks the code!

Research directions

Concurrency tools

- Developers working on large projects follow sequential locking disciplines
  - Sequential analysis to mimic the developer
  - Language constructs to help the developer
- Indirect defects reported on a single thread are much easier to fix

Static & dynamic analysis

- Static followed by dynamic
  - Instrument problem areas using static analysis
  - Gather dynamic traces to diagnose defects
- Dynamic followed by static
  - Use dynamic analysis to create a signature for good execution traces
  - Use static analysis to find execution traces that do not match the signature
- Common intermediate information
  - Code coverage, …

Users as automated testers

- Huge opportunity to improve code quality
  - Find out what's failing, where, how often
  - Diagnose the failures
  - Early warning data
- Avoid falling into the trap of the long awaited "code review editor"
  - Need to find limited, concrete scenarios

Evolutionary tools

- Specification-based tools evolve a language
  - Introduce a programming discipline
  - Increase the portability of legacy code
- We have tackled memory usage
  - Rinse and repeat

Summary

- Program analysis technology can make a huge impact on how software is developed
- The trick is to properly balance research on new techniques with a focus on deployment
- The Center for Software Excellence (CSE) at Microsoft is doing this (well?) today

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