The Semester in Context

Last time
- Dynamic optimizations with DyC

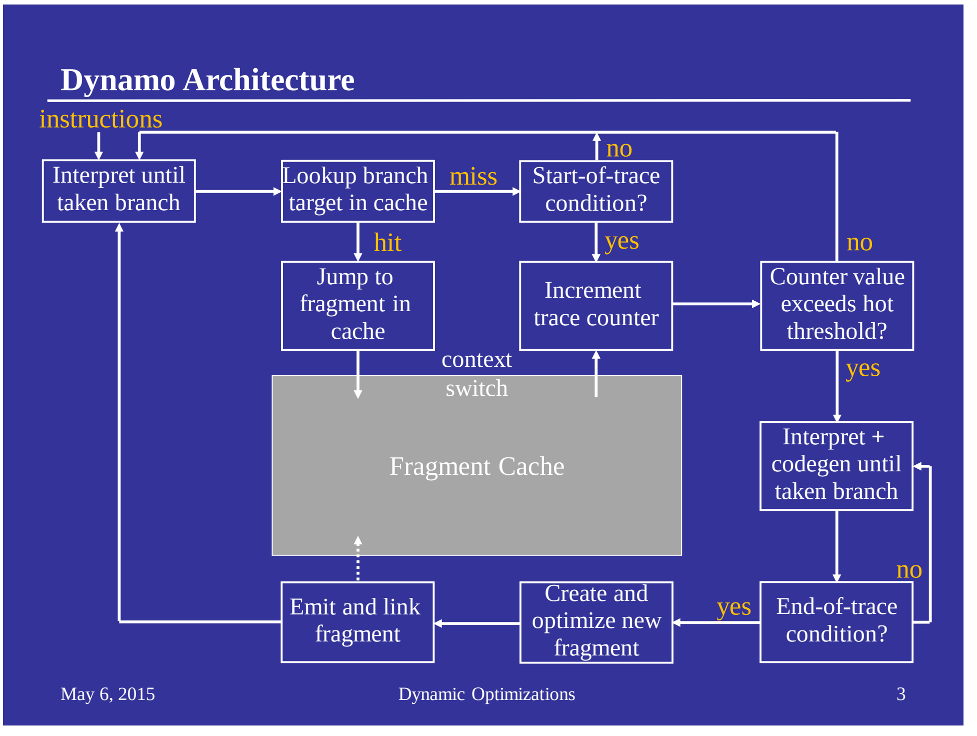
Today
- Dynamo
- DELI
- The big picture

Dynamic Optimization in Dynamo [Bala, *et al.* 2000]

Modern systems create obstacles for static compilers
- Objects, small procedures, dynamically linked libraries

Idea
- Dynamically optimize native binaries
- Transparent to the programmer
  - No annotations

Mechanism
- Interpret instructions } **Slow**
  - Identify hot traces
- Generate native code for traces
  - Optimize these traces
- Cache these traces for future use } **Fast**


Dynamo Architecture
instructions
Interpret until taken branch
Lookup branch target in cache
miss
Start-of-trace condition?
no
hit
yes
no
Jump to fragment in cache
Increment trace counter
Counter value exceeds hot threshold?
context switch
yes
Fragment Cache
Interpret + codegen until taken branch
no
Emit and link fragment
Create and optimize new fragment
yes
End-of-trace condition?
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Dynamic Optimizations
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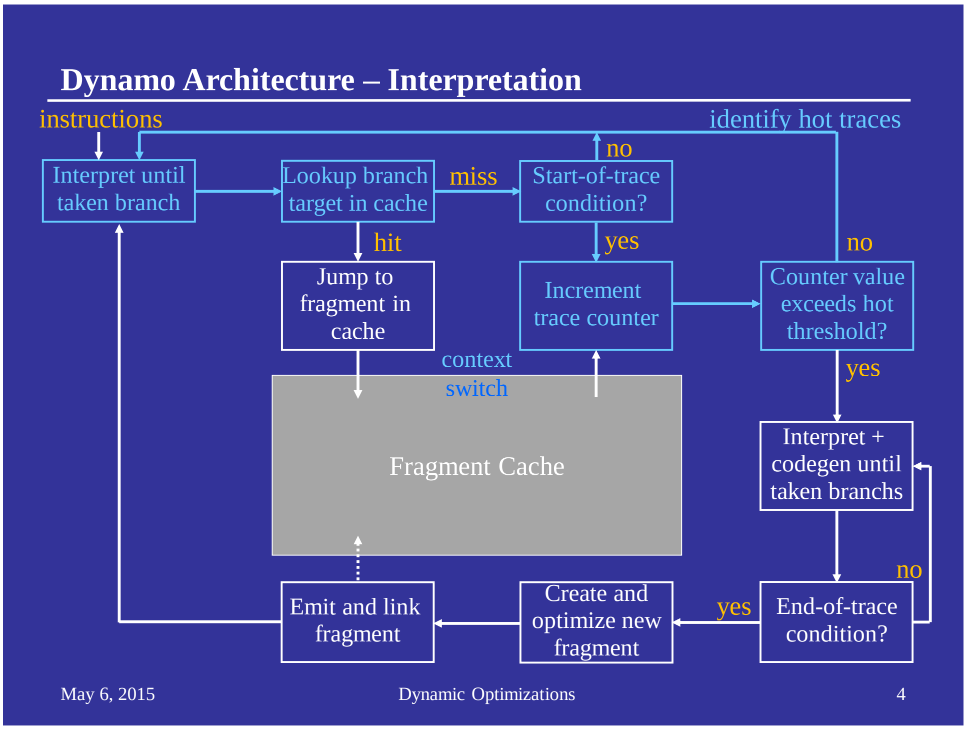
Dynamo Architecture – Interpretation
instructions
identify hot traces
Interpret until taken branch
Lookup branch target in cache
miss
Start-of-trace condition?
no
hit
yes
no
Jump to fragment in cache
Increment trace counter
Counter value exceeds hot threshold?
context switch
yes
Fragment Cache
Interpret + codegen until taken branchs
no
Emit and link fragment
Create and optimize new fragment
yes
End-of-trace condition?
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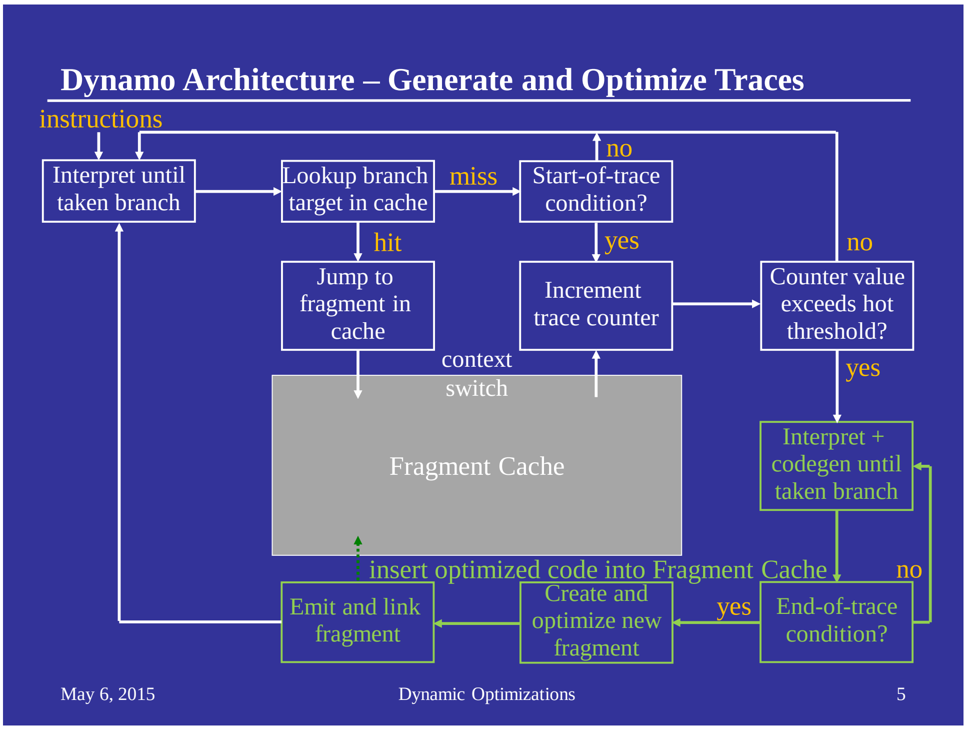
Dynamo Architecture – Generate and Optimize Traces
instructions
Interpret until taken branch
Lookup branch target in cache
miss
Start-of-trace condition?
no
hit
yes
no
Jump to fragment in cache
Increment trace counter
Counter value exceeds hot threshold?
context switch
yes
Fragment Cache
Interpret + codegen until taken branch
insert optimized code into Fragment Cache
no
Emit and link fragment
Create and optimize new fragment
yes
End-of-trace condition?
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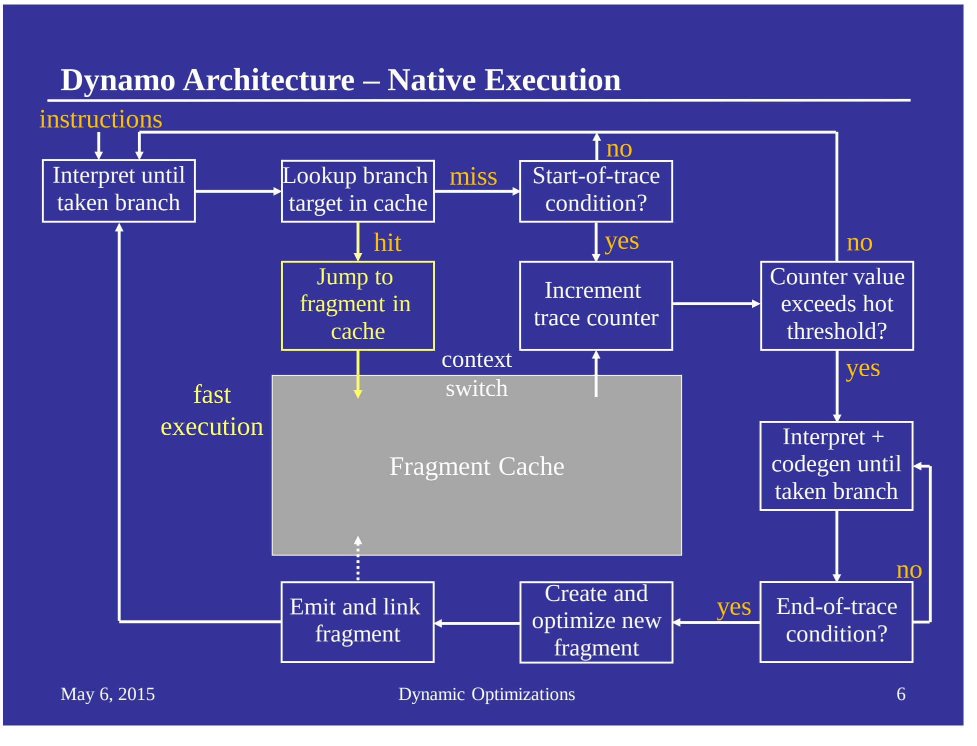
Dynamo Architecture – Native Execution
instructions
Interpret until taken branch
Lookup branch target in cache
miss
Start-of-trace condition?
no
hit
yes
no
Jump to fragment in cache
Increment trace counter
Counter value exceeds hot threshold?
context switch
yes
fast execution
Fragment Cache
Interpret + codegen until taken branch
no
Emit and link fragment
Create and optimize new fragment
yes
End-of-trace condition?
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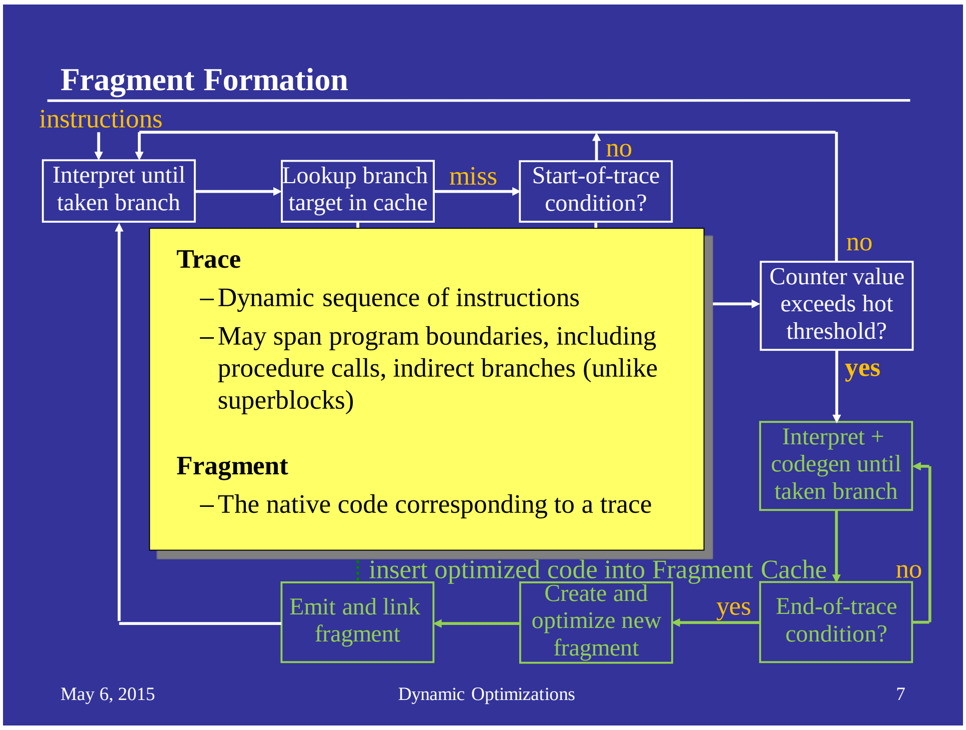
Fragment Formation
instructions
Interpret until taken branch
Lookup branch target in cache
miss
Start-of-trace condition?
no
no
Counter value exceeds hot threshold?
yes
Interpret + codegen until taken branch
Trace
– Dynamic sequence of instructions
– May span program boundaries, including procedure calls, indirect branches (unlike superblocks)
Fragment
– The native code corresponding to a trace
insert optimized code into Fragment Cache
no
Emit and link fragment
Create and optimize new fragment
yes
End-of-trace condition?
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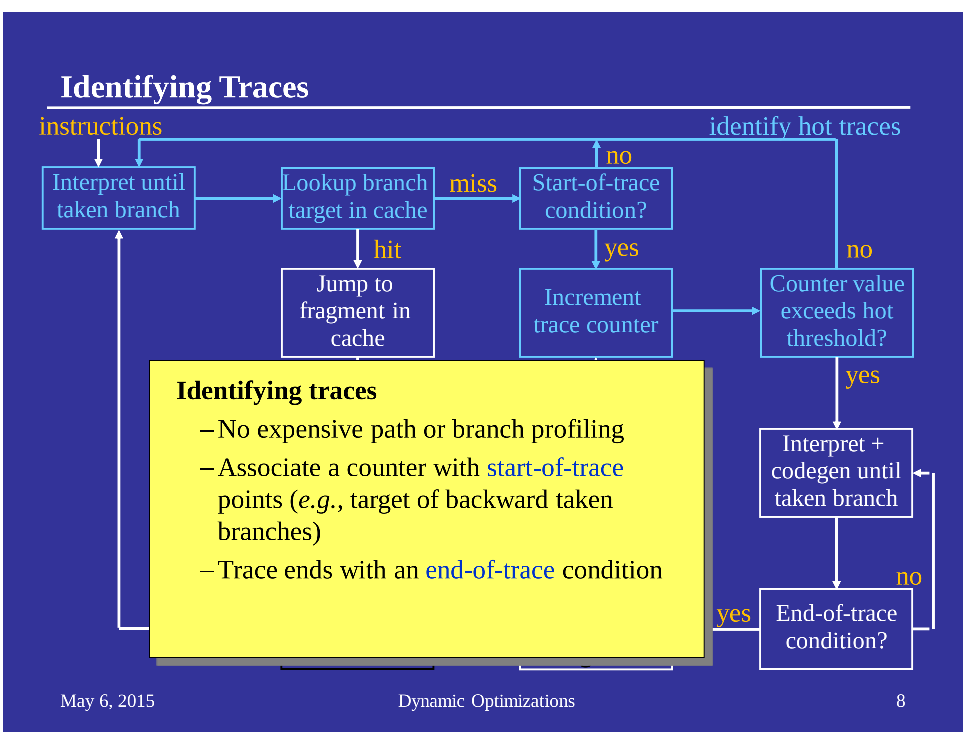
Identifying Traces
instructions
identify hot traces
Interpret until taken branch
Lookup branch target in cache
miss
Start-of-trace condition?
no
hit
yes
no
Jump to fragment in cache
Increment trace counter
Counter value exceeds hot threshold?
yes
Identifying traces
– No expensive path or branch profiling
– Associate a counter with start-of-trace points (e.g., target of backward taken branches)
– Trace ends with an end-of-trace condition
Interpret + codegen until taken branch
no
yes
End-of-trace condition?
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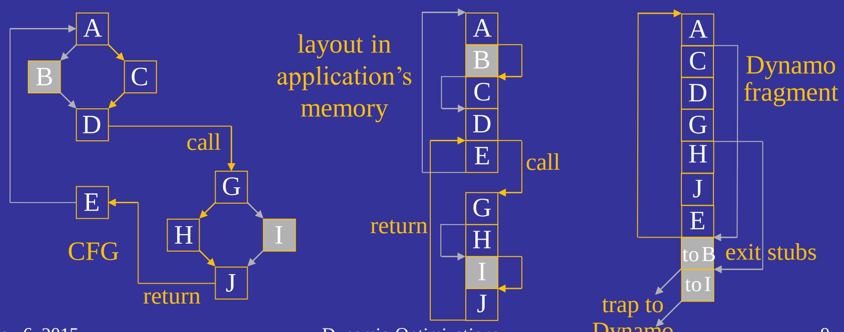
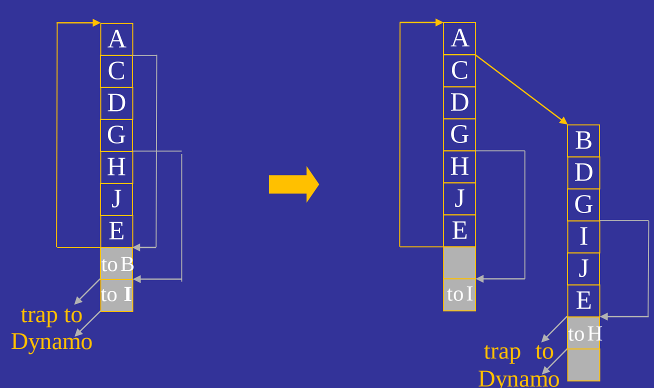
Trace Optimization

Create straightline code fragments
- Remove unconditional branches on the trace
- Remove redundancies exposed by straightening
  - Redundant loads and assignments
  - Copy propagation, constant propagation, strength reduction, loop invariant code motion, loop unrolling



Fragment Linking

Fragments are linked in the Fragment Cache
- Reduces number of exits from the Fragment Cache
- For example, if we create a new fragment B-D-G-I-J-E:



Performance Results

Methodology
- SPEC int 95
- HP C/C++ commercial compiler

Baselines
- Compared against three baselines
  - Intraprocedural optimizations
  - Interprocedural optimizations
  - Interprocedural optimizations + profiling

Results
- About 9% better with intraprocedural optimizations
- About 11% better with interprocedural optimizations
- No improvement for interprocedural optimizations + profiling

Related Work

Trace caches
- Hardware mechanism for caching sequences of decoded instructions

rePLay [Fahs, et al, Micro 2001]
- Pure hardware solution

ICOP [Chou and Shen ISCA 2000]
- Similar to Dynamo but uses a dedicated co-processor to optimize the traces

Dynamo vs. JITs

Isn't Dynamo just like a JIT?

- Both monitor the executing code to see what's hot
- Both cache, link, and execute native optimized code

How are the two different?

- Source language
  - JIT: Java bytecode (language-dependent)
  - Dynamo: native binary (machine-dependent)
- Scope
  - JIT: works largely on method-by-method basis
  - Dynamo: dynamic traces of instructions (no language barriers)

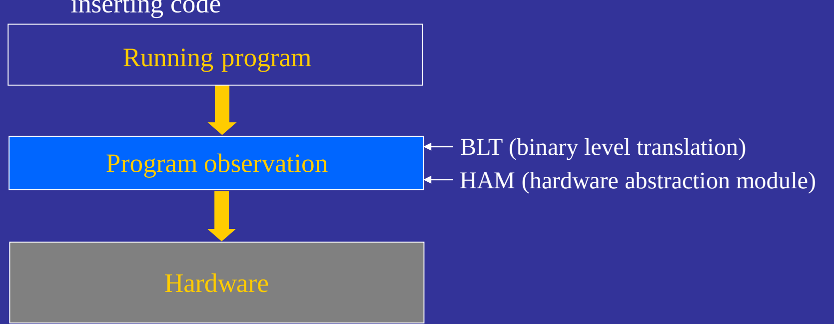
Another difference

- What if we change the source language for Dynamo? Binary emulation

DELI: Successor to Dynamo [Micro'02]

DELI: Dynamic Execution Layer Interface

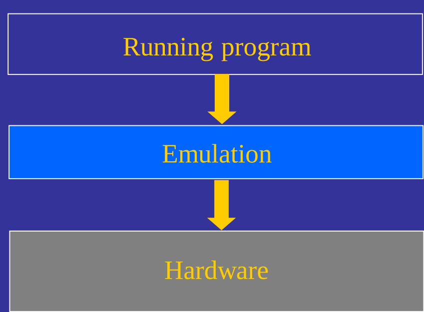
- Generalize the idea of Dynamo
  - Observe every instruction in the running program
  - Provide a new interface for inspecting, modifying, caching, and inserting code



DELI Generalizes a Common Theme

VMWare

- Full-system emulation
  - eg. Run x86 code on a Sparc
  - Fast, transparent



Transmeta

- Emulates x86 code on a VLIW core
  - Flexible: can change underlying hardware while retaining binary compatibility
  - Fast, transparent

DELI Generalizes a Common Theme (cont)

DELI

- Can operate transparently as an emulator
- Can also allow native and emulated code to run together
  - Facilitates incremental migration across platforms and product generations
    - e.g. Streaming media application:
      - Emulate GUI and application
      - Execute native MPEG decoder for fast execution
    - e.g. Can emulate OS code for a hardware
- Can integrate into emulated code software patches as native code

Other Uses of DELI

Code decompression

– Can decompress code before emulation

Security

– Decryption
– Virus detection
– Sandboxing

Installing Untrusted Code

Software sandboxing

– Allow sharing within an address space without compromising safety
– *e.g.*, Install an untrusted module into the kernel

kernel

untrusted code

– System checks that the untrusted module does not overstep its boundaries
  – Checks branch targets
  – Checks addresses of stores
– Provides safety with respect to the memory system

Revisiting the question: DELI vs. JITs

Both provide virtualization

- Both provide a fast path and a slow path
- Why? Reduces effort and overhead
- We see two systems principles at work:
  - Use an extra level of indirection (virtualization)
  - Optimize the common case (native execution for the fast path)

The Larger Trend

Success disaster

- Mark Weiser's vision of ubiquitous computing [1988] is coming true
  - Computing is pervasive
  - Computing is non-invasive
  - Computing is woven into the fabric of our lives
- We rely on huge amounts of hardware and software– whose provenance is unknown– to be correct and secure
- We rely on systems whose complexity is overwhelming

Improving software quality

- Many dimensions to consider . . .

Compatibility

Binary compatibility

- As the legacy code base increases, compatibility becomes increasingly important
- Compatibility is a form of quality
- Two ways to get compatibility
  - Conform to an existing standard
  - Emulation

Correctness

Language trend: "managed code"

- What is managed code?
  - Bounds checks
  - Sandboxing
  - Garbage collection
  - . . .

Safety through language support

- Typesafe languages
- Use modern languages and use type theory to prove that all references are safe

Security

Limit access to system resources

- A generalization of software sandboxing
- Can some untrusted code inappropriately access the file system?
  - Files can have different access privileges, *e.g.*, read, write, execute
- Can some untrusted code inappropriately access the network?
  - *e.g.*, The code can access my digital camera but not my microphone

Privacy

- Does privileged information leak to the outside world?

How can compilers help?

Program Checking

Check for partial correctness

- Does the program terminate?
- Does the program use locks correctly?
- Does the program allow information to leak to the outside world?
- . . .

Program Checking Techniques

Lexical techniques
– Fast, but very superficial (*e.g.* Lint)

Type systems
– Example: add `tainted` type qualifier
– Becoming increasingly sophisticated

Model checking and FSMs
– Precise and detailed analysis
– Suffers from state explosion problem

Formal verification
– Requires full formal specification
– Very expensive and not fully automated

Less precise | Less expensive

DFA

More precise | More expensive

Fault Tolerance

Can we protect a program against transient faults?
– An increasingly important issue as feature sizes shrink
– Can insert code that performs redundant computations and checks for correctness

Program Understanding

Does a program do what it's supposed to do?
- Might it do something that is improper?
- Static analysis is useful here
- Folks at the NSA worry about these kinds of things

Is one program derived from another?
- MOSS: uses static analyses

Does a program contain malware?
- Early work: do simple pattern matching to identify code fragments of known malware
- Use semantic pattern matching (like MOSS)

Protection Against Reverse Engineering

Goal
- Discourage reverse engineering
- More important with the use of bytecodes, which contain considerable information

Solutions
- Physically restrict access to code
- Encrypt code– tends to limit portability because of special hardware needs
- Code obfuscation
  - Make it more costly to reverse engineer a program

Program Obfuscation

Name obfuscation

- Scramble the names of identifiers (*eg.* C Shroud)

Data obfuscation

- Change the way that data is encoded
  - *e.g.* Replace `i` by `8*i+3`

```
int i = 1;                 int i = 11;
while (i<1000) {           while (i<8003) {
. . . A[i] . . .;          . . . A[(i-3)8] . . .;
   i++;                       i += 8;
}                          }
```

  - *e.g.* Add indirection to access array elements
- Change the organization of data
  - *e.g.* Convert a 2D array into a 1D array

Program Obfuscation (cont)

Control obfuscation

- Disguise control flow
  - Inline procedures
  - Reverse order of loops
  - Insert irrelevant statements (dead code)
  - Dismantle high level constructs
    - e.g. Java has no `goto` statement, but the `bytecode` does

Program Obfuscation (cont)

Control obfuscation

- Opaque Predicates [Collberg, et al,'98]
  - Predicates whose values are opaque to static analysis
- Idea
  - Leverage the complexity of alias analysis and shape analysis
  - Insert code that manipulates nodes of a tree or a graph
  - Maintain invariants about specific pointers into the graph
    - eg. p != q
    - Use comparisons of these pointers as opaque predicates

```
if (p==q)
    // fake code
else
    // real code
```

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Code Size

Embedded Code

- Runs on embedded hardware with limited memory
- Code size is an issue

Two solutions

- Code compression
  - Requires decompression
- Code compaction
  - Produce binaries that are small (yet still executable)
  - Standard optimizations on binary code (CSE, constant propagation…)
  - Code re-factoring
    - Find sequences of common code
    - Put these into new procedures
    - Trades off increased execution time for reduced space

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Concepts

Dynamic compilation
- Runtime constants
- Staged compilation
- Native binary optimization
- Identifying and optimizing commonly executed code fragments

Many dimensions of software quality
- Compatibility
- Correctness
- Security
- Opaqueness
- . . .

Next Time

Final exam
- 9:00am Saturday May 16th GDC 4.304
- You may bring one 8.5” × 11” page of notes (double-sided)

Project deadline
- Sunday May 17th, 5:00pm
- Stay tuned to Piazza for details about presentations