Dynamic Analysis

Martin Kellogg

Reading Quiz: dynamic analysis

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Q2: **TRUE** or **FALSE**: the authors describe an infinite loop that CHESS detected in a research operating system

- it was a spin loop that didn't do anything, but it was not infinite

Agenda: dynamic analysis

- **motivation and terminology**
- instrumentation
- properties of dynamic analysis
- real example analyses

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  - **testing itself!**
  - computing coverage
  - detecting likely invariants (Daikon)
  - etc.

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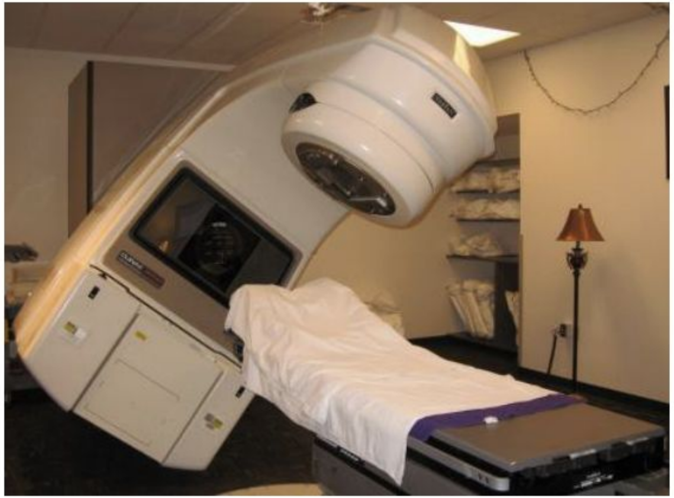
key questions for today:

- what are some **common features** of dynamic analyses?
- what else can we **do** with dynamic analysis?

An example: race conditions & Therac-25

- Radiation therapy machine for treating cancer



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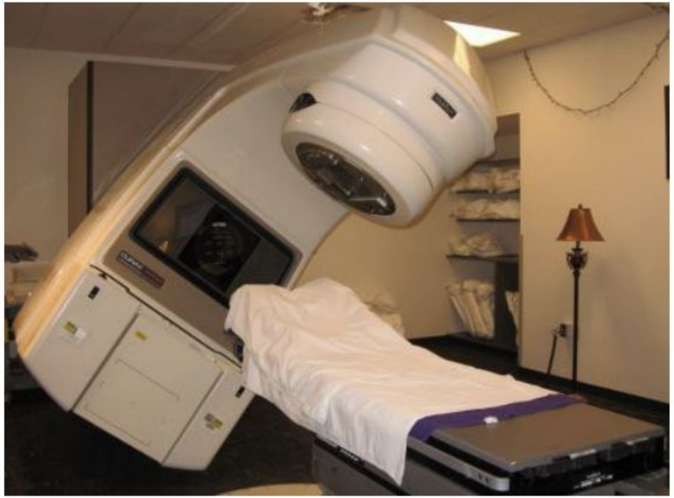

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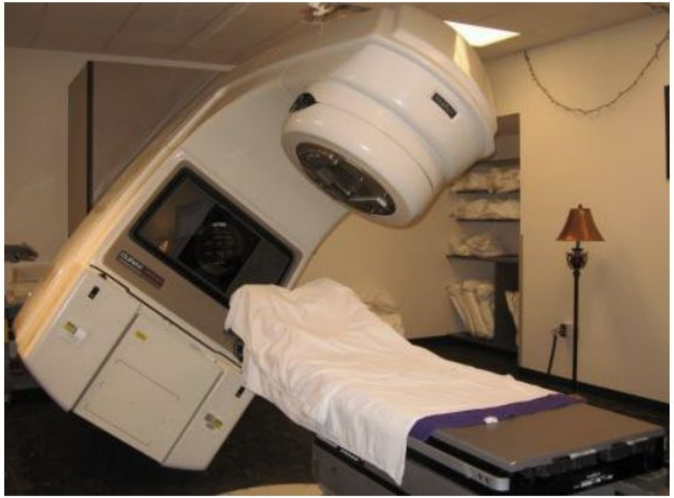
- Radiation therapy machine for treating cancer
- At least six accidents between 1985 and 1987 in which patients were given **massive overdoses** of radiation
- Because of concurrent programming errors (**race conditions**!), it sometimes gave its patients radiation doses that were hundreds of times greater than normal, resulting in death or serious injury



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- How can we detect a race condition?
    - testing? code review? **run the program with a special scheduler that we control?!?**

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These difficult questions could all be answered by **running the program** in **controlled conditions** (i.e., by a dynamic analysis):

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These difficult questions could all be answered by **running the program** in **controlled conditions** (i.e., by a dynamic analysis):

- Does this program have a race condition?
- Does this program run quickly enough?
- How much memory does this program use?
- Is this predicate an invariant of this program?
- Does this test suite cover all of this program?
- Can an adversary's input control this variable?
- How resilient is this distributed application to failures?

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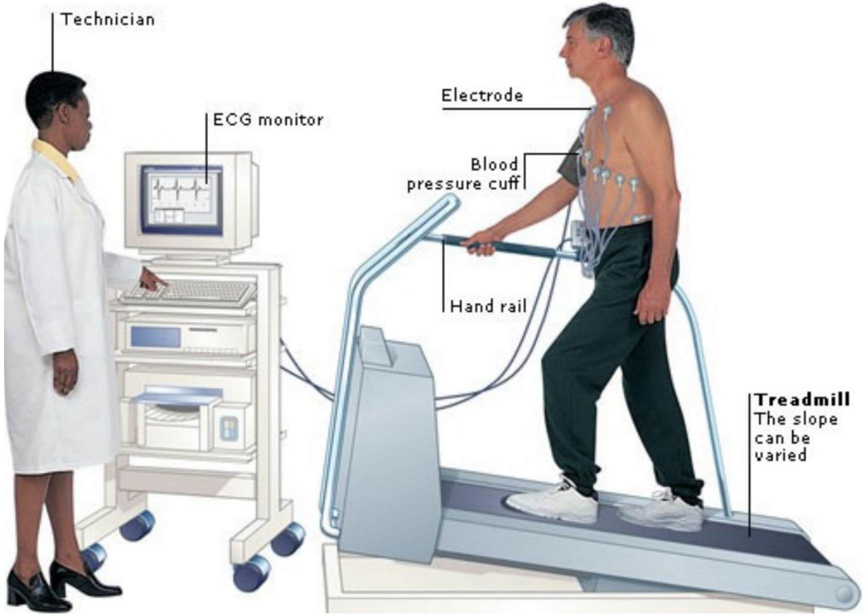
- Suppose that we want to find out about your heart.
  - Just looking at you (i.e, your "source code") may not be fully informative.
  - We hook you up to electrodes, have you walk a special treadmill, and look at the results.



Dynamic analysis: common structure

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    - **Instrument** the program: capture data to learn more than "pass/fail"

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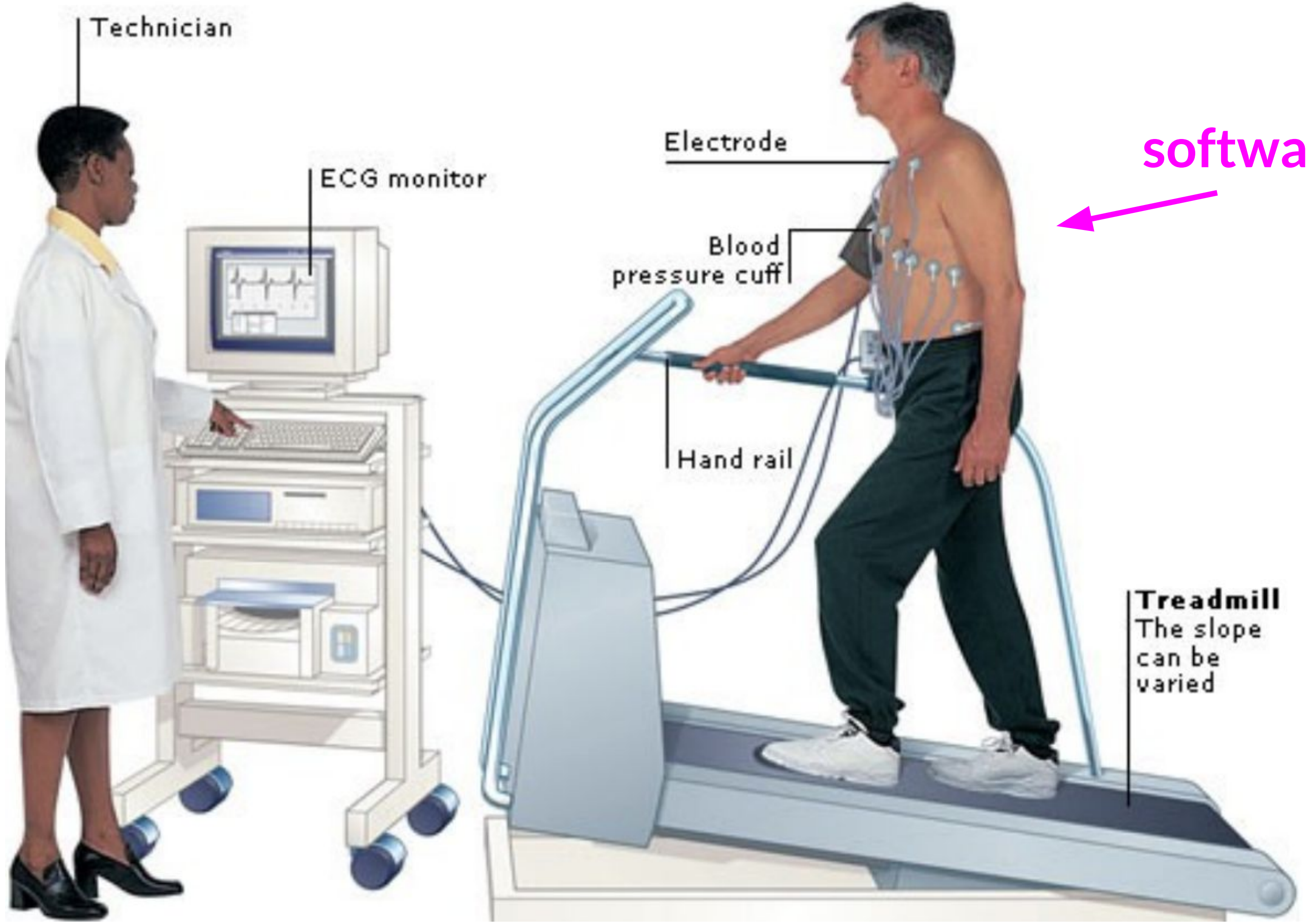
- Monitor internal state at runtime
  - Instrument the program: capture data to learn more than “pass/fail”
- Analyze the results


Technician
ECG monitor
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The slope can be varied

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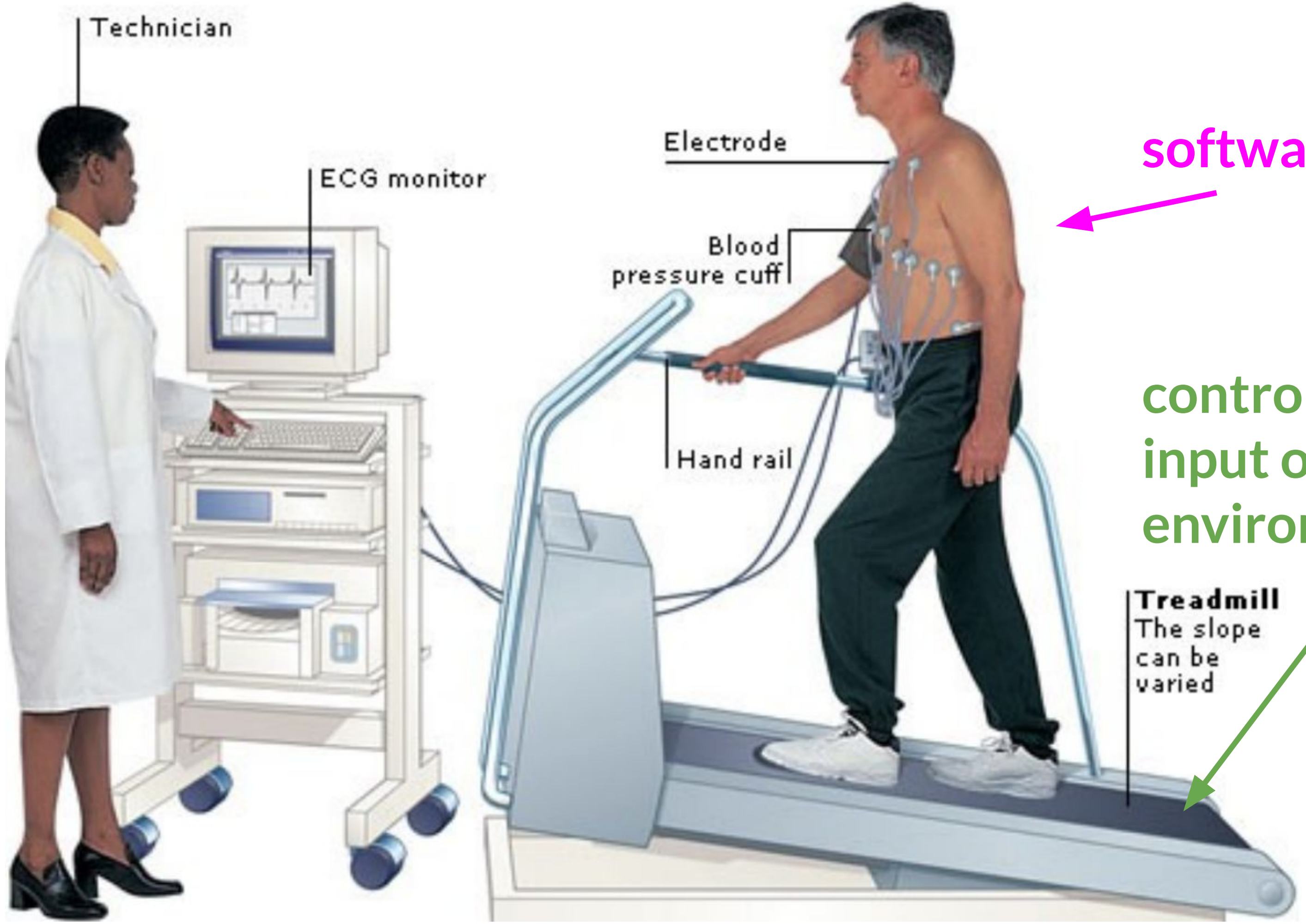

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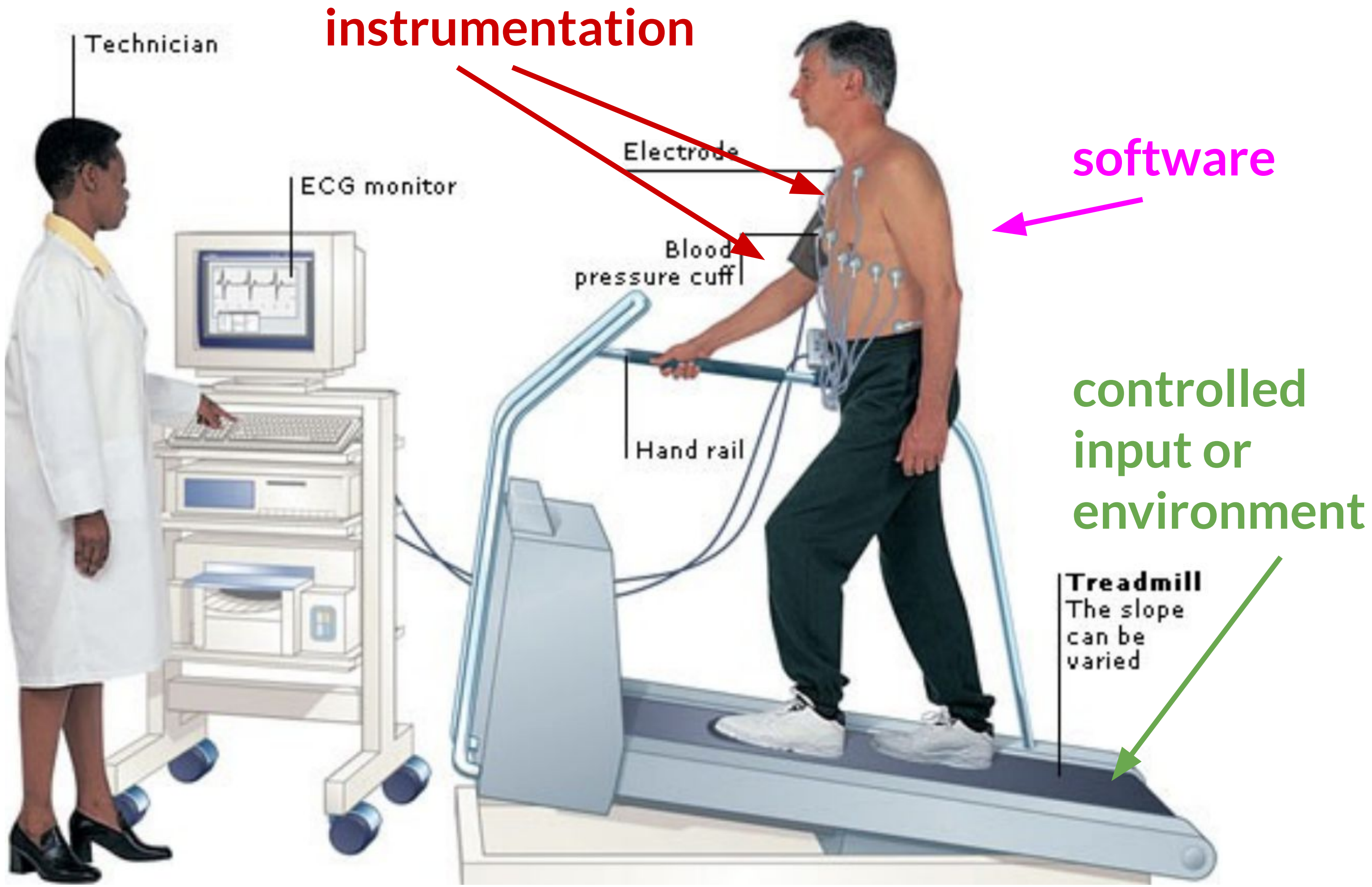
controlled input or environment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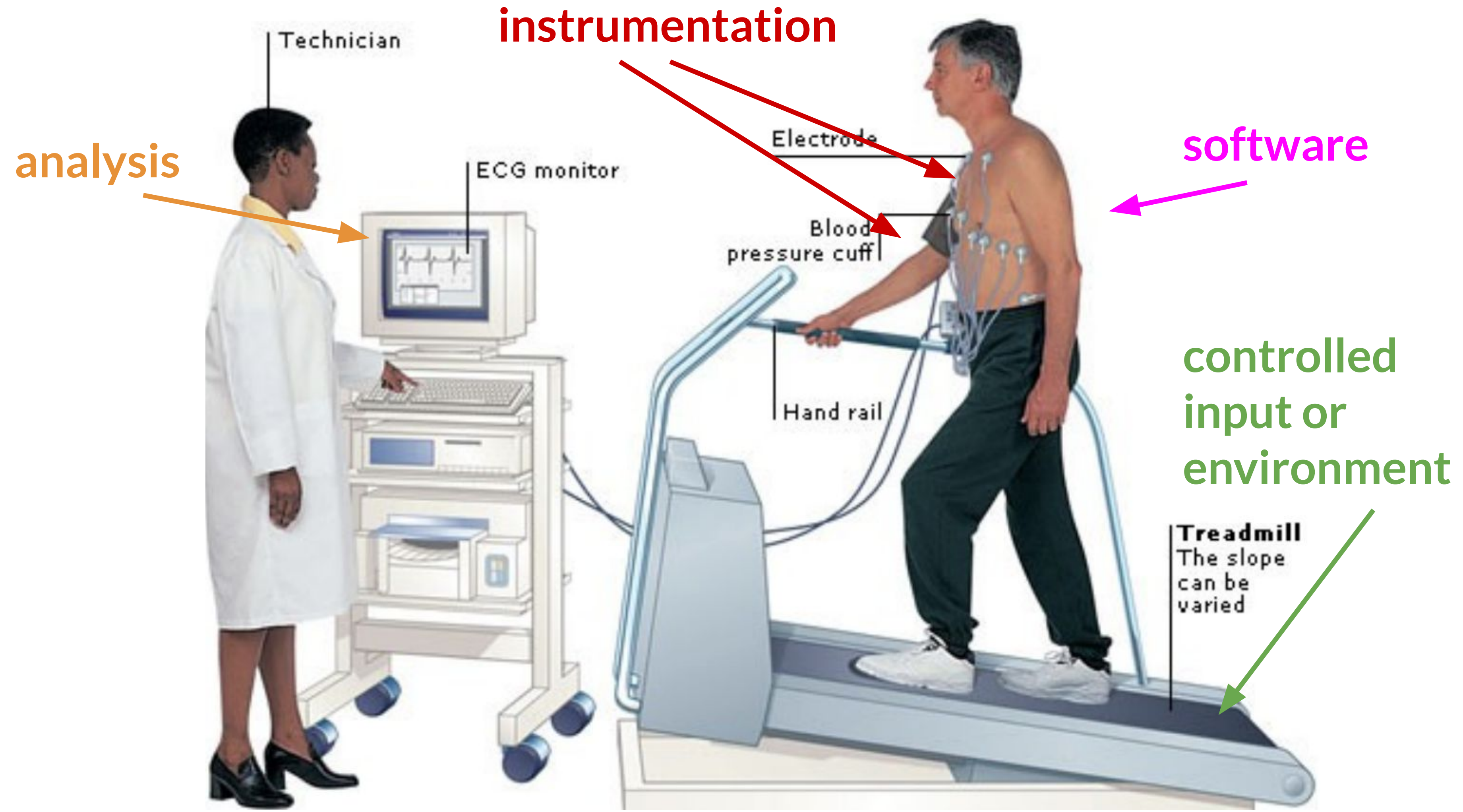
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A **common student pitfall**: confusing what happens at **compile time** ("preparing the program to record information") and what happens at **run time** ("actually recording the information")

- You instrument the program *before* running it

Example: path coverage

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- You want to determine how many times each **acyclic path** in a method is executed on a given test input.
  - How do you change the program to record information that will allow you to discover this?
- How do you do it for this example? **In-class exercise in pairs**:

```
if (a < b) { foo(); } else { bar(); }
if (c < d) { baz(); } else { quoz(); }
```

Example: path coverage: instrument edges

```
P: if (a < b) {
      Q: count["P->Q"]++; foo(); }
   else {
      R: count["P->R"]++; bar(); }
S: if (c < d) {
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   else {
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Example: path coverage: inst

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Suppose:

- P→Q = 2
- P→R = 4
- S→T = 3
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How many times was P->Q->S->T taken?

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a	b	c	d
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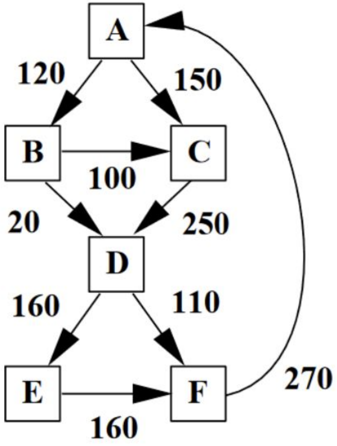
1 time!

Example: edge counts vs. path profiles



Path	Prof1	Prof2
ACDF	90	110
ACDEF	60	40
ABCDF	0	0
ABCDEF	100	100
ABDF	20	0
ABDEF	0	20

Figure 1. Example in which edge profiling does not identify the most frequently executed paths. The table contains two different path profiles. Both path profiles induce the same edge execution frequencies, shown by the edge frequencies in the control-flow graph. In path profile $Prof1$, path $ABCDEF$ is most frequently executed, although the heuristic of following edges with the highest frequency identifies path $ACDEF$ as the most frequent.

[*Efficient Path Profiling.* T. Ball and J. Larus. MICRO 1996.]

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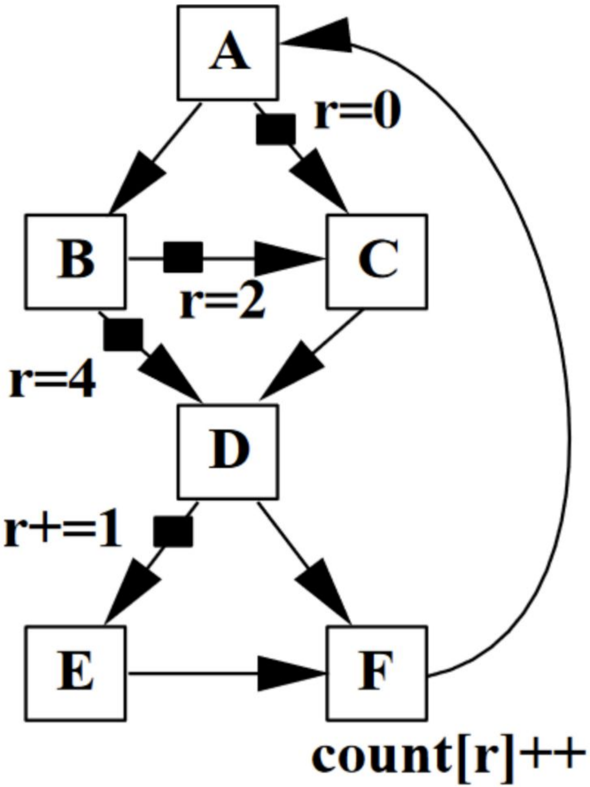

Path	Encoding
ACDF	0
ACDEF	1
ABCDF	2
ABCDEF	3
ABDF	4
ABDEF	5

Note: uses only 1 variable, 4 integer assignments and 1 memory update. But handles ~8 edges!

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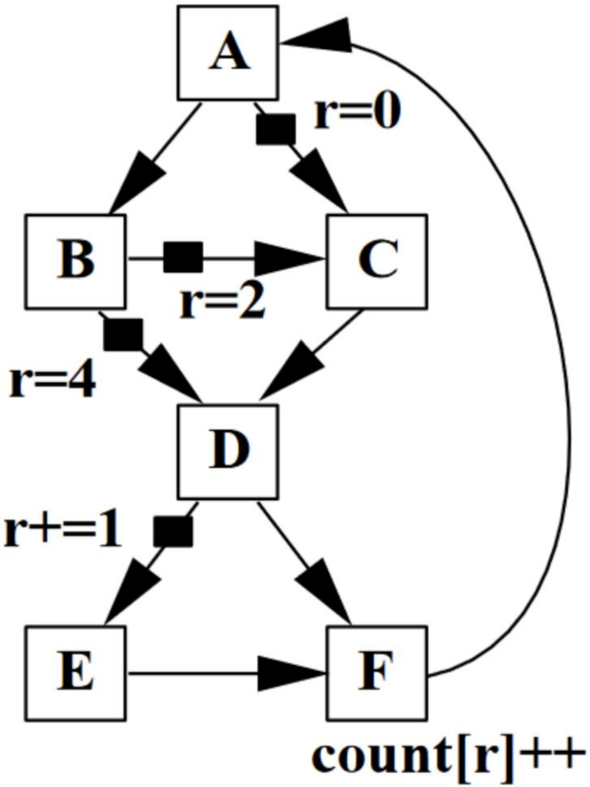

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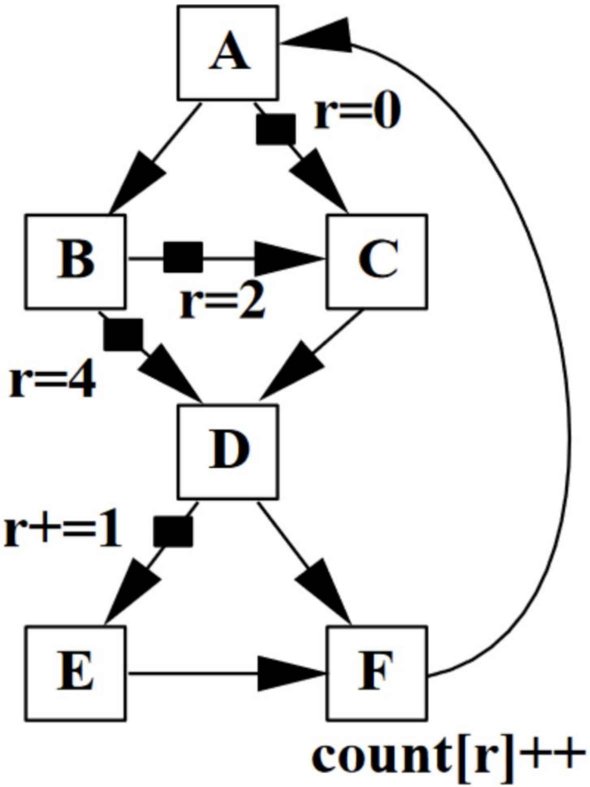

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could we do even better?

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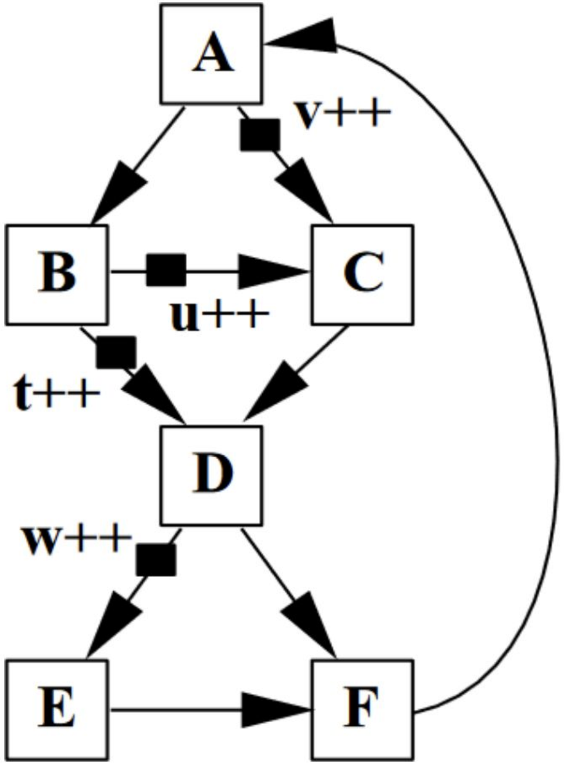

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E -> F	=	w
A -> B	=	t + u
F -> A	=	t + u + v

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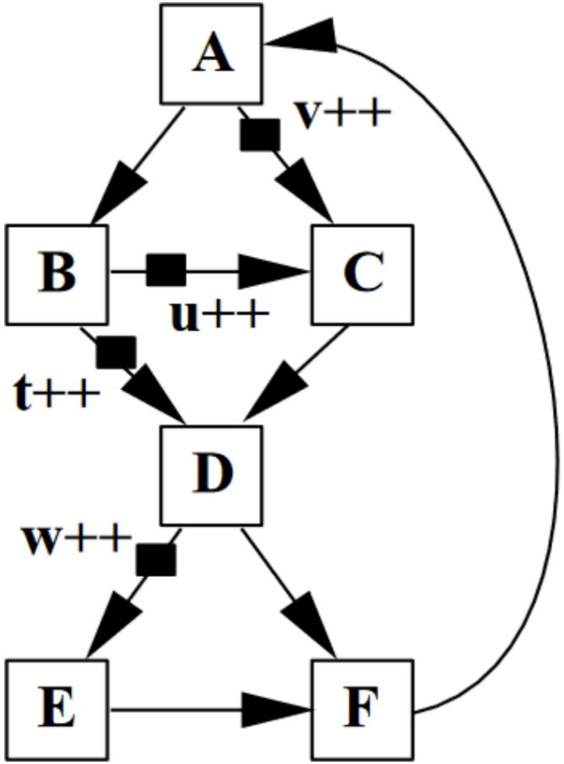

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these smart approaches are 2.8x faster, etc.

Another example: information flow tracking

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Two important definitions:

- ***Sources*** are where sensitive information enters the program (e.g., input from the network, user passwords, time of day, etc.)
- ***Sinks*** are untrusted communication channels or sensitive computations (e.g., SQL commands, text displayed in the clear, etc.)

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Consider the following program:

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var user = $_POST[“user”];
var passwd = $_POST[“passwd”];
var posts = db.getBlogPosts();
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- Conceptually:
  - record time at entry and exit of each method
  - subtract
  - update global table
- In practice, complex enough to merit a whole lecture!
  - we don’t have time to cover this in detail, but feel free to ask me about it!

Dynamic analyses: commonalities

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Key question for us: what do they have **in common**?

- they all involve **recording a subset** of all information about the program's execution

Dynamic analyses: what to record

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- How fast is a modern SSD?
  - As of January 2022, the fastest SSD drives offered ~7000 MB/s write speeds

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- Must focus on a **particular property** or type of information
  - abstract a trace of execution rather than recording the entire state space
    - "most problems in computer science can be solved by adding either a layer of abstraction or a cache"

Components of a dynamic analysis

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- **Property** of interest
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- **Property** of interest
  - *What are you trying to learn about? Why?*
- **Information** related to property of interest
  - *How are you learning about that property?*

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Example: branch coverage components

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  - *Postprocess, discard duplicates, divide observed # by total #*

Agenda: dynamic analysis

- motivation and terminology
- **instrumentation**
- properties of dynamic analysis
- real example analyses

Instrumentation: nuts and bolts

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Instrumentation: nuts and bolts

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```
P: if (a < b) {
        Q: count[“P->Q”]++; foo(); }
   else {
        R: count[“P->R”]++; bar(); }
S: if (c < d) {
        T: count[“S->T”]++; baz(); }
   else {
        U: count[“S->U”]++; quoz(); }
```

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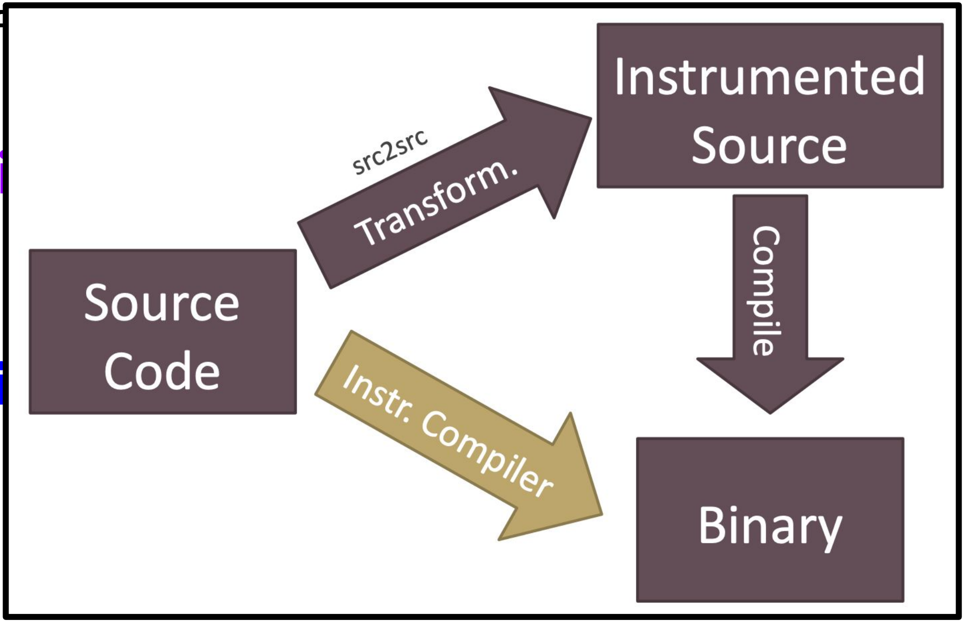

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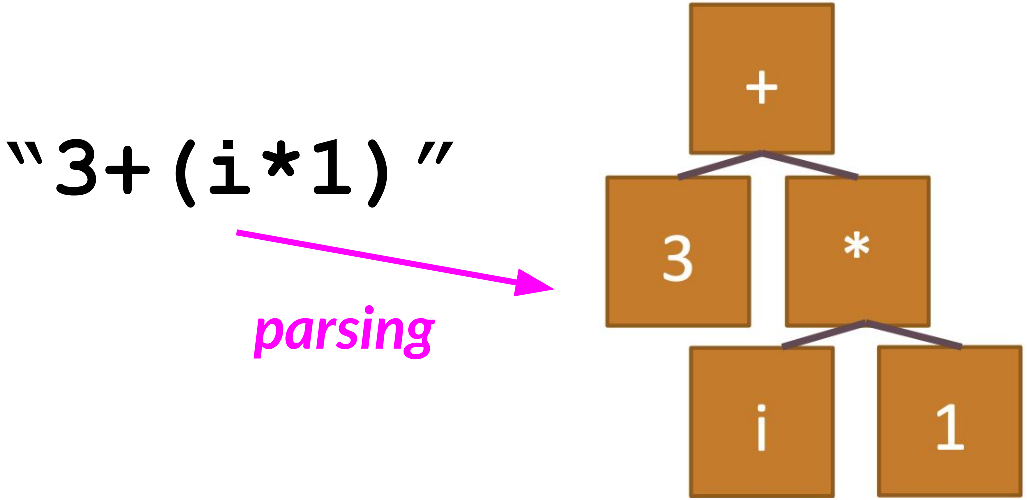

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Note that this is an AST, like the ones you're using for HW6

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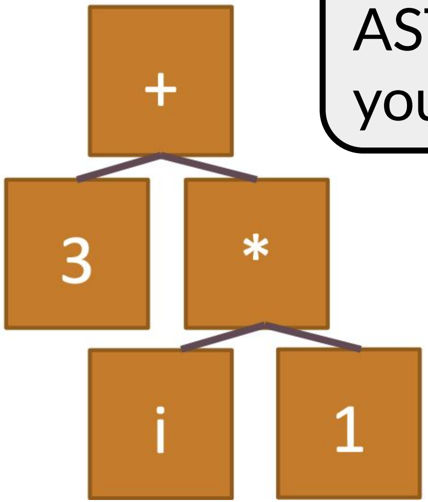
parsing



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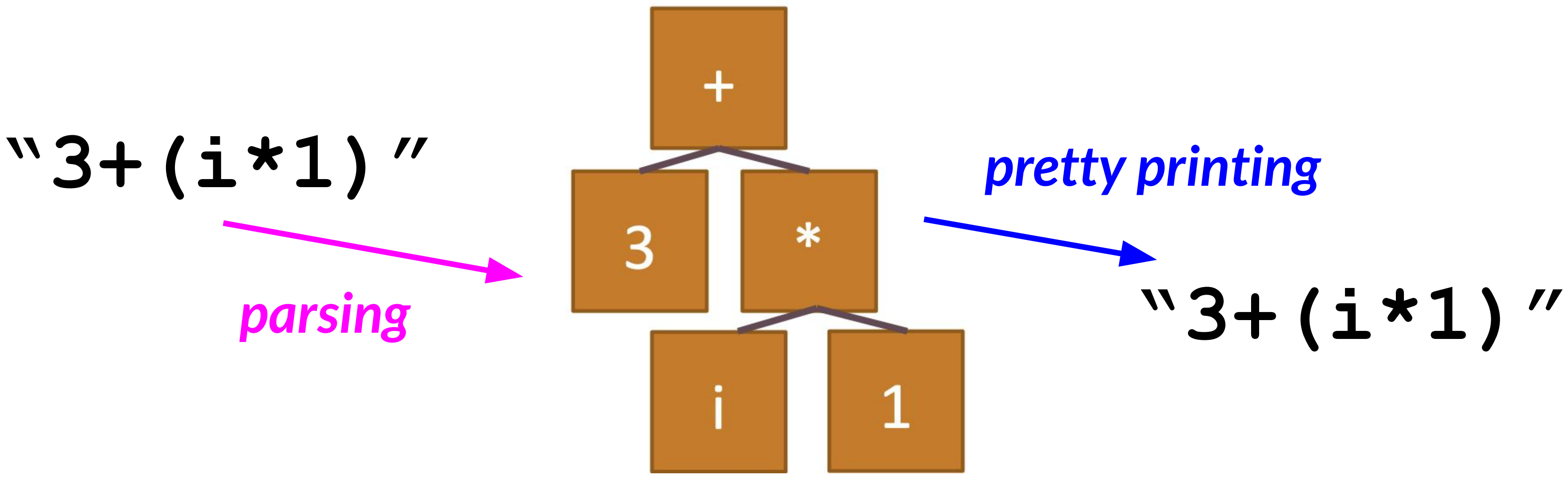

Instrumented compilers: AST rewriting

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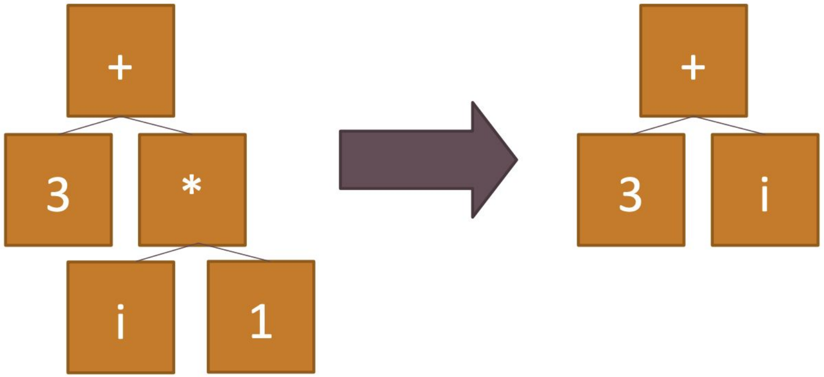
  - Visitors, pattern matchers, etc., exist



Instrumented compilers: AST rewriting

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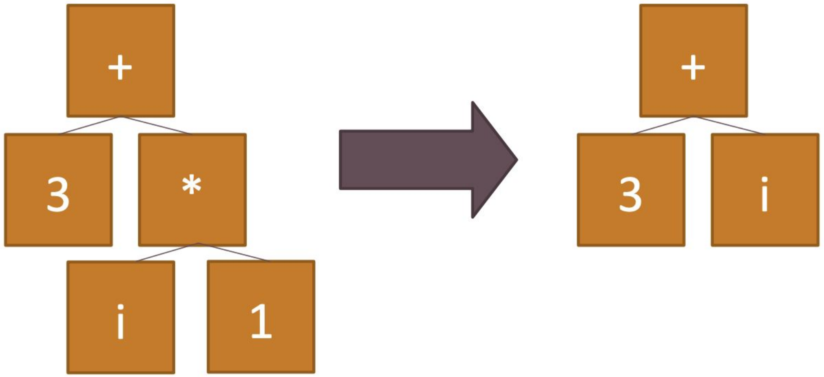
- You are already doing AST rewriting in HW6 for mutation testing; the basic concept for instumentation is the same



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    - Load, push, pop values from variables to stack
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Instrumented compilers: binary rewriting

- It is also possible to rewrite a compiled binary, object file or class file
- Java Byte Code is the Java VM input
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  - Load, push, pop values from variables to stack
  - Similar to x86 assembly (but much nicer!)
- Java AST vs. Java Byte Code
  - You can transform back and forth (lose comments)
  - Ask me about **obfuscation**!

Instrumented compilers: byte code example

- Method with a single int parameter:
    - **`ALOAD 0`**
    - **`ILOAD 1`**
    - **`ICONST_1`**
    - **`IADD`**
    - **`INVOKEVIRTUAL “my/Demo” “foo” “(I)Ljava/lang/Integer;”`**
    - **`ARETURN`**

Instrumented compilers: JVM specification

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    - e.g., Apache Commons Byte Code Engineering Library "is intended to give users a convenient way to analyze, create, and manipulate (binary) Java class files (those ending with .class). Classes are represented by objects which contain all the symbolic information of the given class: methods, fields and byte code instructions …"

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Key point: your compiler and runtime are ***just like other libraries***, and treating ***code as data*** is relatively easy!

Instrumented compilers: example rewrites

Instrumented compilers: example rewrites

- Check that every parameter of every method is non-null
- Write the duration of the execution of every method into a file
- Report a warning on Integer overflow
- Use a connection pool instead of creating every database connection from scratch
- Add in counters and additions to track path or branch coverage
  - How do you think `gcov` works?
- etc.

Instrumentation: other approaches

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- Virtual machines and emulators
  - Valgrind, IDA Pro, GDB, etc.
  - Selectively rewrite running code or add special instrumentation (e.g., software breakpoints in a debugger)

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- Generic Instrumentation Tools
  - Aspect-Oriented Programming

Agenda: dynamic analysis

- motivation and terminology
- instrumentation
- **properties of dynamic analysis**
- real example analyses

Dynamic analysis: costs and limitations

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- Performance **overhead** for recording
  - Acceptable for use in testing?
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  - “Heisenbugs” vs. “Ship what you test”
- Accuracy
  - False **positives**?
  - False **negatives**?

Aside: false positives and false negatives

Can X **actually** happen?

YES	NO

Aside: false positives and false negatives

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Useful tool for thinking about anything that might warn us about a problem

Aside: soundness and completeness

Sound Analyses:

- Report all defects → **no false negatives**
- Typically **overapproximate** possible behavior
- Are “conservative” with respect to safety: when in doubt, say it is unsafe

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Sound Analyses:

- Report all defects → **no false negatives**
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Complete Analyses:

- Every reported defect is an actual defect → **no false positives**
- Typically **underapproximate** possible behavior

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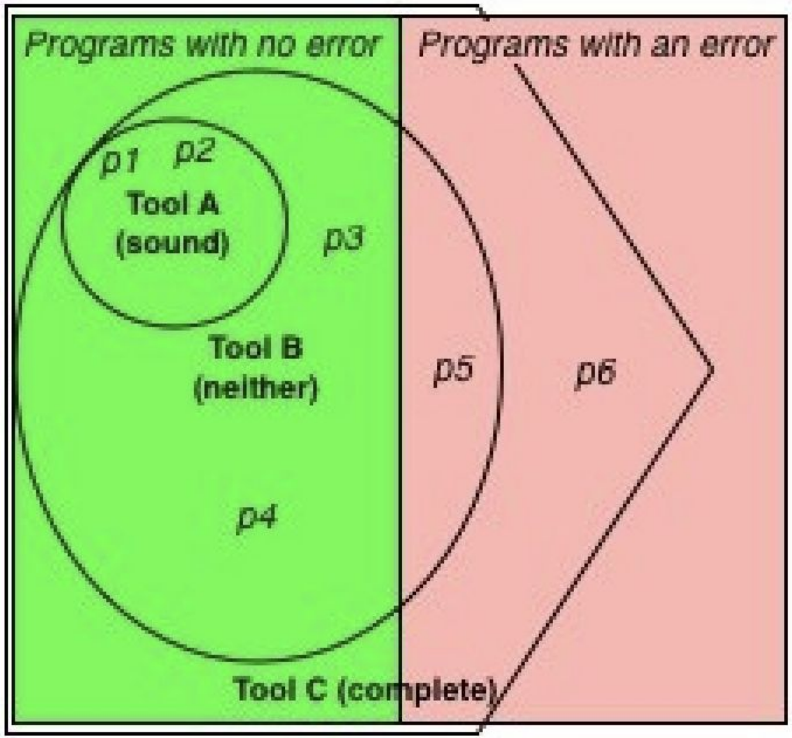
"You can trust me when I say your radiation dosing software is safe."



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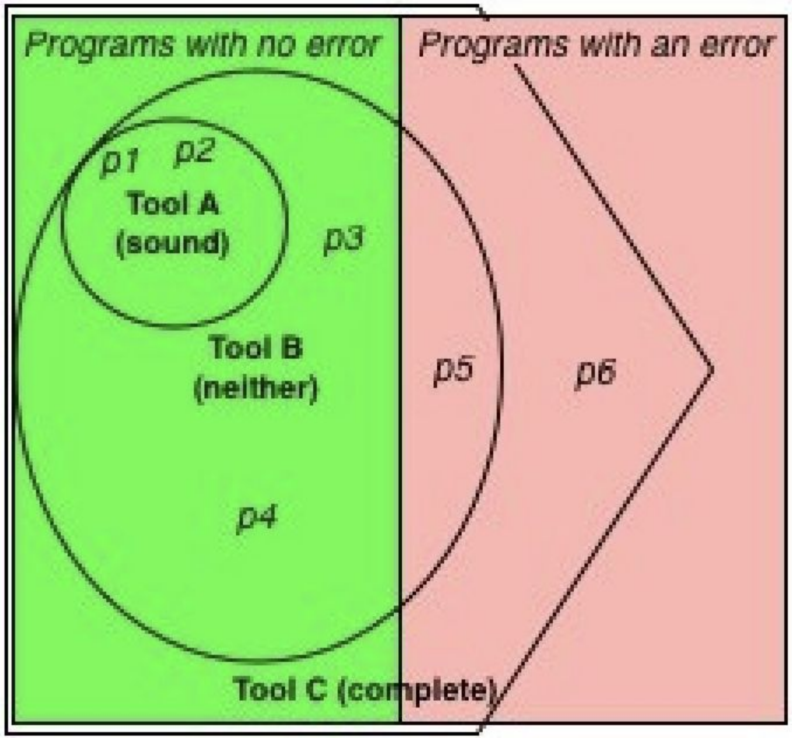

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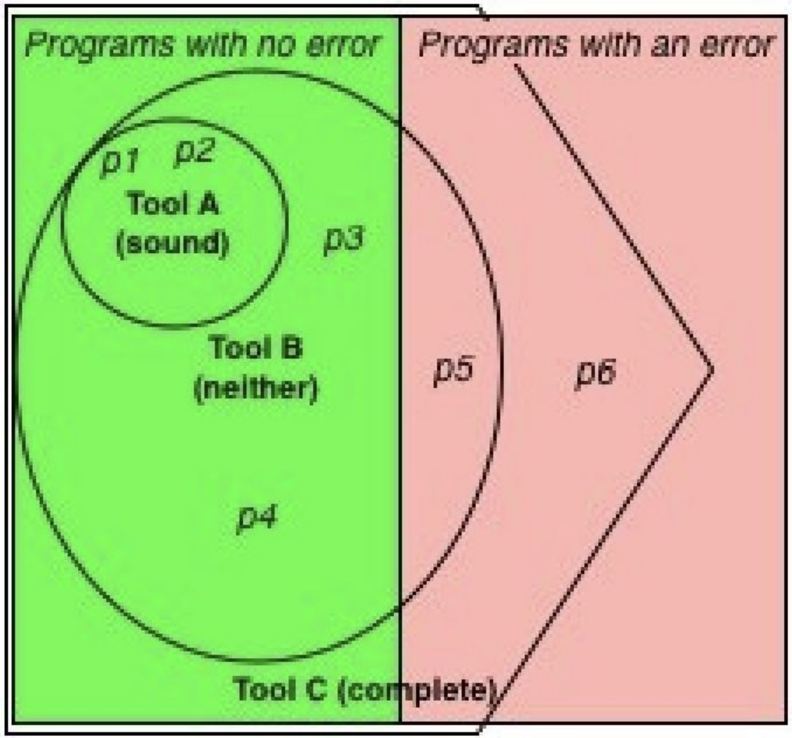

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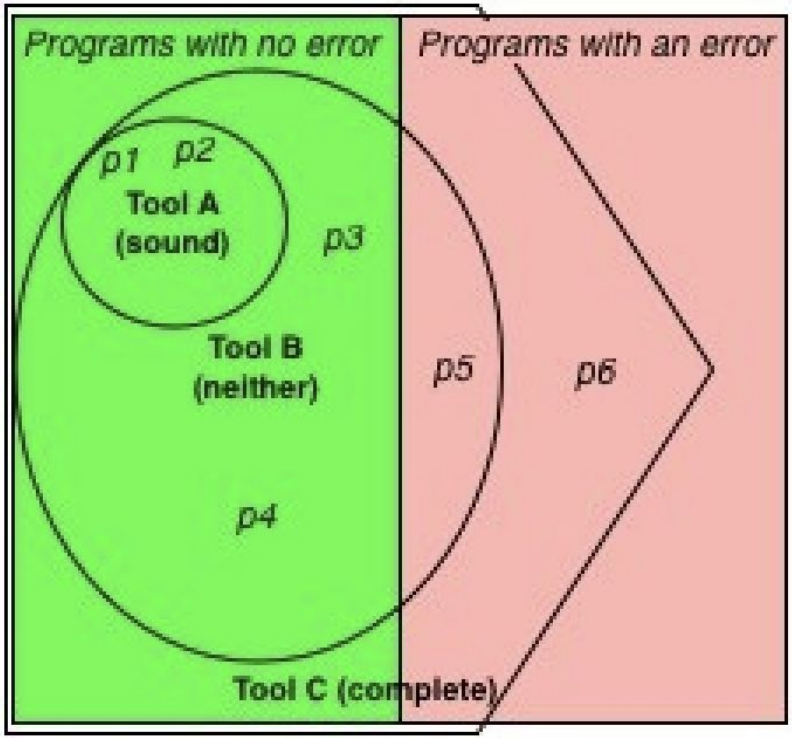

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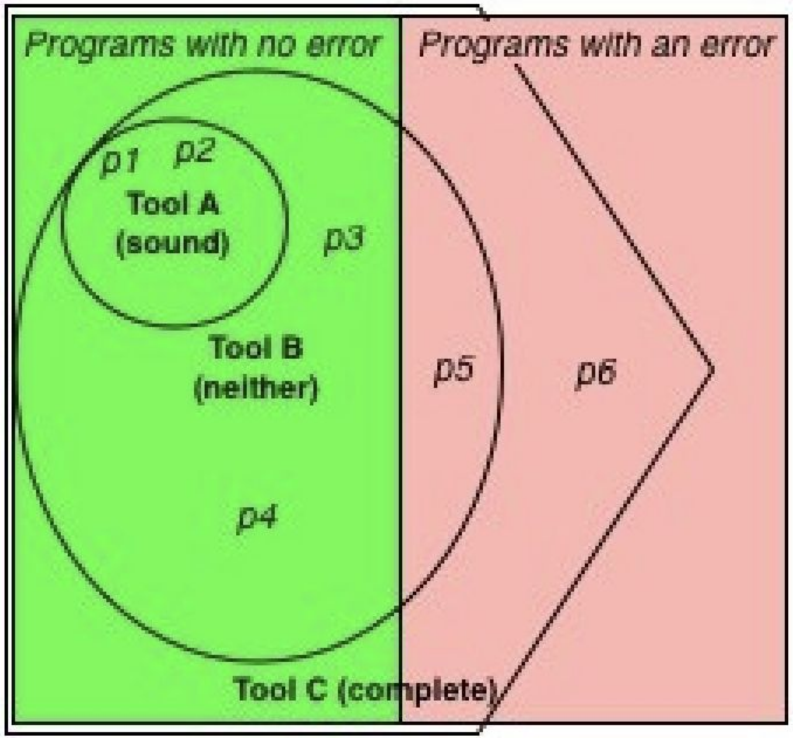
  - But C may say unsafe P5 is actually safe!



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  - so they can't be both sound and complete

Dynamic analysis: soundness vs completeness

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  - completeness! Dynamic analyses generally underapproximate program behavior by reasoning about only the program executions that they actually observe.
- we'll discuss ***static analyses*** (i.e., program analyses that don't require us to run the program) after spring break
  - traditionally, many static analyses are designed to be sound

Dynamic analysis: input dependence

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- Are those tests **indicative of normal use**?
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- Are those tests specific inputs that replicate **known defect** scenarios?
  - (e.g., memory leaks or race conditions)

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- caused by the **observer effect**: instrumentation and monitoring can change the behavior of a program
    - through slowdown, memory overhead, etc.
- two considerations about instrumentation + the observer effect:
    - consideration 1: can/should you deploy it **live**?
    - consideration 2: will instrumentation **meaningfully change** the program’s behavior wrt the property you care about?

Agenda: dynamic analysis

- motivation and terminology
- instrumentation
- properties of dynamic analysis
- **real example analyses**

Examples of real dynamic analyses

- Digital Equipment Corporation's **`Eraser`**
- Netflix's **`Chaos Monkey`**
- Microsoft's **`CHESS`**
- Microsoft's **`Driver Verifier`**

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Eraser: is there a race condition?

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// Thread #1
while (true) {
    lock(mutex);
    v := v + 1;
    unlock(mutex);
}
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// Thread #2
while (true) {
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No race condition!

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```

```
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while (true) {
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}
```

Race condition! consider what happens if thread 1 holds mu1 and thread 2 holds mu2…

Eraser: Insight: Lockset Algorithm

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    - Start with "all locks could possibly protect ***v***"
    - If you observe that lock ***m*** is not held when you access ***v***, remove lock ***m*** from the set of locks that could possibly guard ***v***
    - If the set of locks that could possibly guard ***v*** is **ever empty**, then no lock can guard ***v***, so you can have a race condition (even if you didn't actually see the race this time!)

Eraser: Lockset Example

Program	*locks_held*	*C(v)*
	`{}`	`{mu1,mu2}`
`lock(mu1);`		
	`{mu1}`	
`v := v+1;`		
		`{mu1}`
`unlock(mu1);`		
	`{}`	
`lock(mu2);`		
	`{mu2}`	
`v := v+1;`		
		`{}`
`unlock(mu2);`		
	`{}`	

Fig. 3. If a shared variable is sometimes protected by **mu1** and sometimes by lock **mu2**, then no lock protects it for the whole computation. The figure shows the progressive refinement of the set of candidate locks $C(v)$ for v. When $C(v)$ becomes empty, the Lockset algorithm has detected that no lock protects v.

[*Eraser: A Dynamic Data Race Detector for Multithreaded Programs.* Savage, Burrows, Nelson, Sobalvarro, Anderson. ACM Trans. Comp. Sys. 15(4) 1997.]

Eraser: Does it work?

- “Applications typically slow down by a factor of 10 to 30 while using Eraser.”
- “It can produce false alarms.”
- Applied to web server (mhttpd), web search indexing engine (AltaVista), cache server, and distributed filesystem
- One example: cache server is 30KLOC C++, 10 threads, 26 locks
  - Eraser detected a “serious data race” in fingerprint computation

Examples of real dynamic analyses

- Digital Equipment Corporation's **`Eraser`**
- Netflix's **`Chaos Monkey`**
- Microsoft's **`CHESS`**
- Microsoft's **`Driver Verifier`**

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- *"Imagine a monkey entering a "data center", these "farms" of servers that host all the critical functions of our online activities. The monkey* ***randomly*** *rips cables, destroys devices and returns everything that passes by the hand. The challenge for IT managers is to* ***design the information system*** *they are responsible for* ***so that it can work despite these monkeys****, which no one ever knows when they arrive and what they will destroy."*

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Chaos Monkey

- *“We have created Chaos Monkey, a program that randomly chooses a server and disables it during its usual hours of activity. Some will find that crazy, but we could not depend on the random occurrence of an event to test our behavior in the face of the very consequences of this event.*

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- **Doctor Monkey** taps into health checks that run on each instance as well as monitors other external signs of health (e.g. CPU load) to detect unhealthy instances and remove them
- **10–18 Monkey** (short for "Localization-Internationalization") detects configuration and run time problems in instances serving customers in multiple geographic regions, using different languages and character sets

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CHESS: Intuition

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- Suppose you have some AVL tree balancing code with a bug
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  - Is there also a small tree that shows it off?
- Suppose you have a concurrency bug that you can show off with a complicated sequence of 16 thread interleavings and preemptions
  - Is there also a sequence of one or two preemptions to show off the same bug? Likely!

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"**CHESS** is a tool for **finding and reproducing Heisenbugs** in concurrent programs. CHESS repeatedly runs a concurrent test ensuring that every run takes a different interleaving. If an interleaving results in an error, CHESS can reproduce the interleaving for improved debugging. CHESS is available for both managed and native programs."

CHESS: does it work?

- *"a lightweight and effective technique for dynamically detecting data races in kernel modules … **oblivious to the synchronization protocols** (such as locking disciplines) … This is particularly important for low-level kernel code …*

[*Effective Data Race Detection for the Kernel.* Erickson, Musuvathi, Burckhardt, Olynyk. OSDI 2010.]

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Driver Verifier: basic plan

What if you instrumented your program to call this instead of open():

```
def my_open(filename, mode):
 if coin_toss(low_probability):
   raise IOError
 elif coin_toss(low_probability):
   raise OSError
 else:
   return open(filename, mode)
```

Driver Verifier: overview

- "***Driver Verifier*** is a tool included in Microsoft Windows that **replaces the default operating system subroutines** with ones that are specifically developed to catch device driver bugs. Once enabled, it **monitors and stresses drivers** to detect illegal function calls or actions that may be causing system corruption."

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    - Simulates low memory, I/O problems, IRQL problems, DMA checks, I/O Request Packet problems, power management, etc.

Driver Verifier: did it work?

- “The Driver Verifier tool that is included in every version of Windows since Windows 2000”
- Microsoft: over 70% of “blue-screen-of-death” (BSOD) crashes caused by 3rd-party drivers
  - they run in the kernel
- Anecdotally, Windows produces many fewer BSOD than it used to
  - but Driver Verifier isn’t the only reason; SLAM/Static Driver Verifier was also an important success; other reasons

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- Dynamic analysis limitations include **efficiency**, **false positives** and **false negatives**.
- Many companies use dynamic analyses, especially for hard-to-test bugs (e.g., concurrency).

Announcements + HW

- Recall there is an exam during the next class (after spring break)
    - Recall that you will be permitted to bring one letter-sized piece of paper with **handwritten** notes (double-sided)
    - Exam day (3/21) schedule:
        - 6 to ~7: intro to static analysis lecture
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Why is the exam in the 2nd half of class? 3/21 is during Ramadan; sunset is at ~7:10 on 3/21.

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- Remainder of today's class: continue working on HW6
    - if you have not yet submitted at least once to Gradescope, you are behind where you should be by this point