Systems vs. Programs

… and The Battle Against Bugs

George Candea
School of Computer & Communication Sciences
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Outline

- Systems Research
- The S2E Platform
- Three Use Cases

What Is A Systems Researcher?

- *Alto personal computer (1972)*
- *Ethernet (1973)*
- *Mesa programming language (1975)*
- *Bravo text editor (1973)*
- *Interpress language (1980)*
- *Fast RPC (1987)*
- *Autonet (1987)*
- *Virtual book (1994)*

Butler Lampson

Systems Challenges

- #1 Challenge: Complexity
  - *e.g., preconditions & postconditions*
- #1 Problem: poorly understood connections
  - *unexplained interference -> loss of predictability*
  - *need predictability in order to achieve scalable performance, reliable operation, etc.*

Some Systems Solutions

- Caching
  - *improve performance by adding another layer*
- Transactions
  - *building blocks for robust systems*
- Virtual Machines
  - *isolation taken to the max (processes, addr spaces, ...)*

Systems Approach

- Get idea
- Build prototype
- Measure & observe
- Adjust prototype ... repeat previous step

- Principles of system construction
  - *modularity, hierarchy, layering, abstraction, end to end*

The Battle Against Bugs

- Bugs = huge source of unpredictability
  - *... your favorite scary bug story here ...*
  - *small discontinuities have significant effects*
- We have no choice but resort to faith

010011010011
110101001010
010010000001
010111010011
110110010110
011011000011

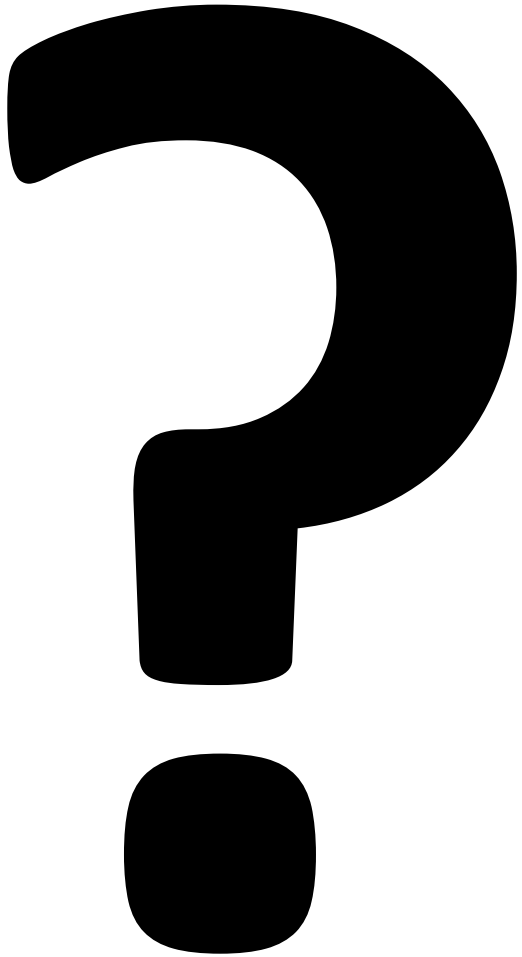
RTL8029.SYS

Computer image courtesy of the Hudson Library & Historical Society

The Rigorous Approach

- Specify, model, and verify
  - *what you run is not what you verify*
- SLAM @ Microsoft
  - *models are hard to get right and to maintain*

Bug-free programs ⇏ Bug-free systems



A Systems Approach

- If cannot take rigorous constructive approach
  - *at least understand in-depth the artifacts we build*
- Build tools to understand systems
  - *performance profilers, debuggers, tracers, ...*
- How to build sophisticated analyzers cheaply?
  - *that work for real systems*

Outline

- ~~Systems Research~~
- The S2E Platform
  - *Background*
  - *S2E: The Theory*
  - *S2E: The System*
- Three Use Cases

S^2E = platform for building

analysis tools that are

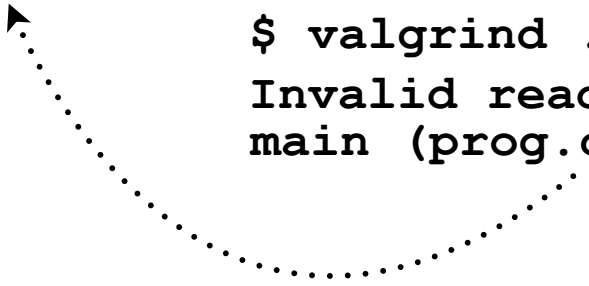
multi-path and

in-vivo

Example of Analysis: Testing

```
int main(argc, argv)
{
  if (argc == 2)
    printf("%c", *argv[2]);

  printf("OK");
}
```

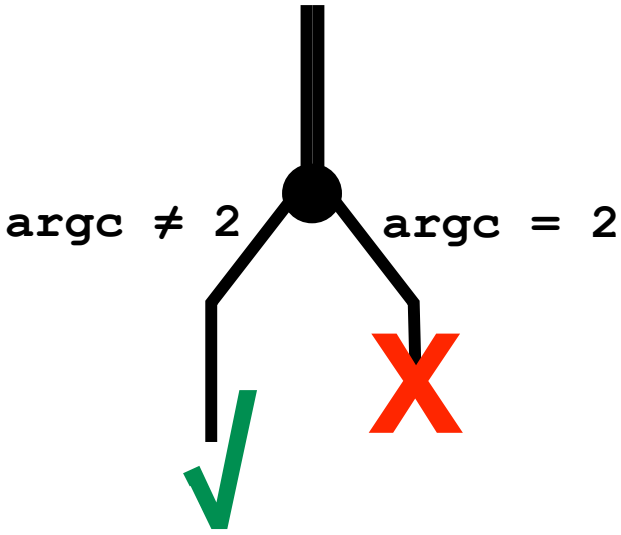
```
$ ./prog
OK

$ ./prog ABC
Segmentation fault

$ valgrind ./prog ABC
Invalid read of size 1
main (prog.c:4)
```



Analysis = check properties of execution paths

Multi-Path Analysis

```
int main(argc, argv)
{
  if (argc == 2)
    printf("%c", *argv[2]);

  printf("OK");
}
```



Simultaneously analyze multiple paths

In-Vivo Analysis

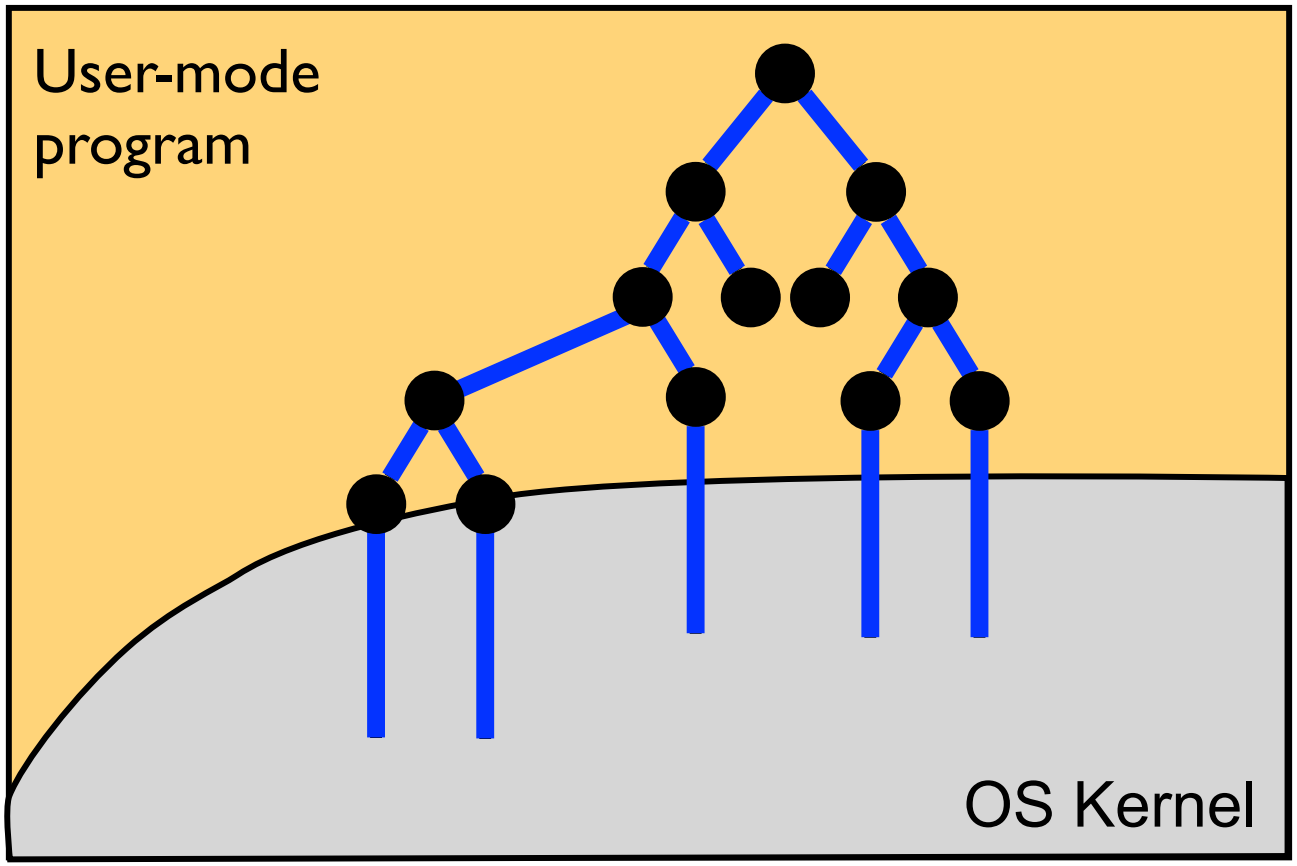
In Vitro

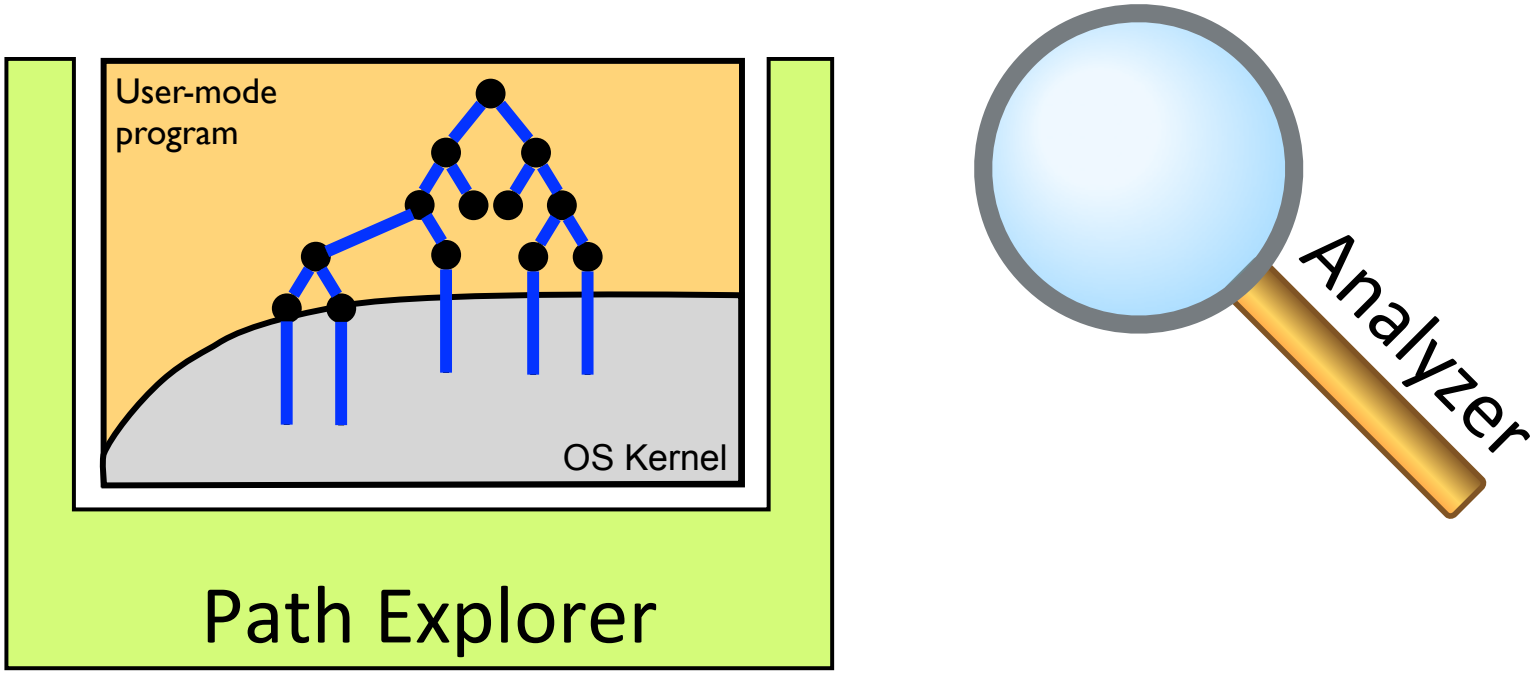
In Vivo

Analyze entire software stack

~~Single-Path In-Vitro~~

Multi-Path In-Vivo





S²E platform = path exploration + path analysis

Challenge #1: Path Explosion

$$\#\ \text{of paths} \approx 2^{\text{system size}}$$

- Cannot analyze all paths ⇒ select only some
  - which paths you choose can make a big difference

Challenge #2: No Source Code

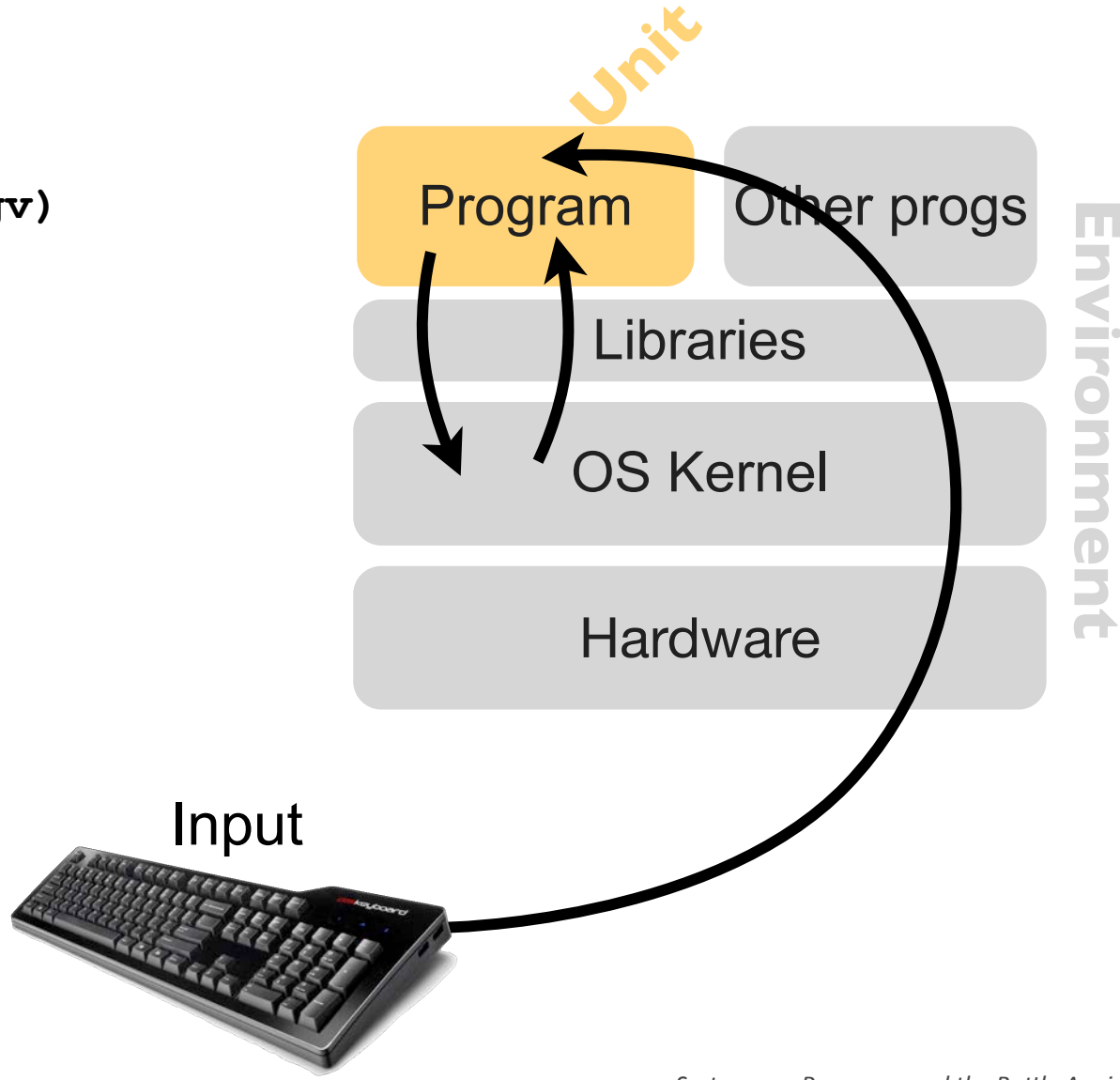
- A lot of interesting software is closed-source
- Systems are built from many pieces
  - *even if you had source code, it would be a pain*
- Solution: analyze machine code
  - *the problem becomes even harder*
  - *more stuff to analyze, loss of type information, etc.*

Outline

- ~~Systems Research~~
- The S2E Platform
  - ~~*Background*~~
  - *S2E: The Theory*
  - *S2E: The System*
- Three Use Cases

System = Unit + Environment

```
int main(argc, argv)
{
  if (argc == 0) {
     ...
  }
  p = malloc(...);
  if (p == NULL) {
     ...
  }
}
```



Thorough Automated Testing


```
int main(argc, argv) {
  if (argc == 0) {
     ...
  }
  p = malloc(...);
  if (p == NULL) {
     ...
  }
  ...
}
```

Unit

Environment

Thorough Automated Testing

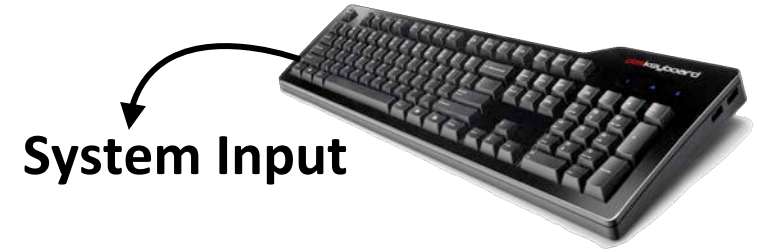
System Input

```
int main(argc, argv) {

  if (argc == 0) {
     ...
  }

  p = malloc(...);

  if (p == NULL) {
     ...
  }
  ...
}
```

Unit

Environment

Thorough Automated Testing




```
int main(argc, argv) {
  if (argc == 0) {
     ...
  }
  p = malloc(...);
  if (p == NULL) {
     ...
  }
  ...
}
```

Unit

Environment

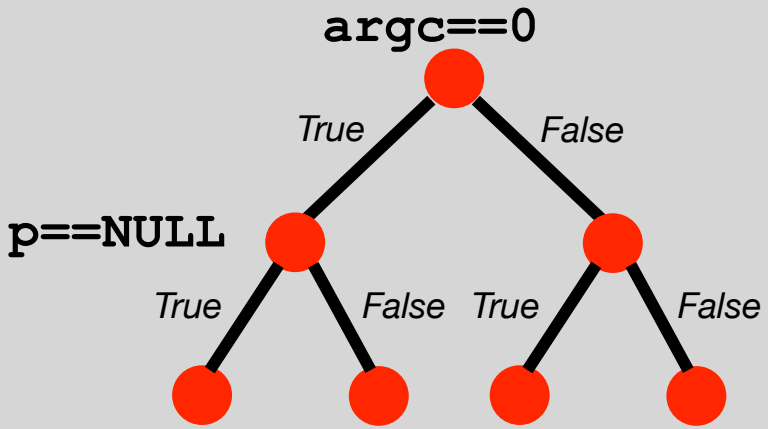
Thorough Automated Testing

Zero false negatives

Zero false positives

```
int main(argc, argv) {
  if (argc == 0) {
     ...
  }
  p = malloc(...);
  if (p == NULL) {
     ...
  }
  ...
}
```

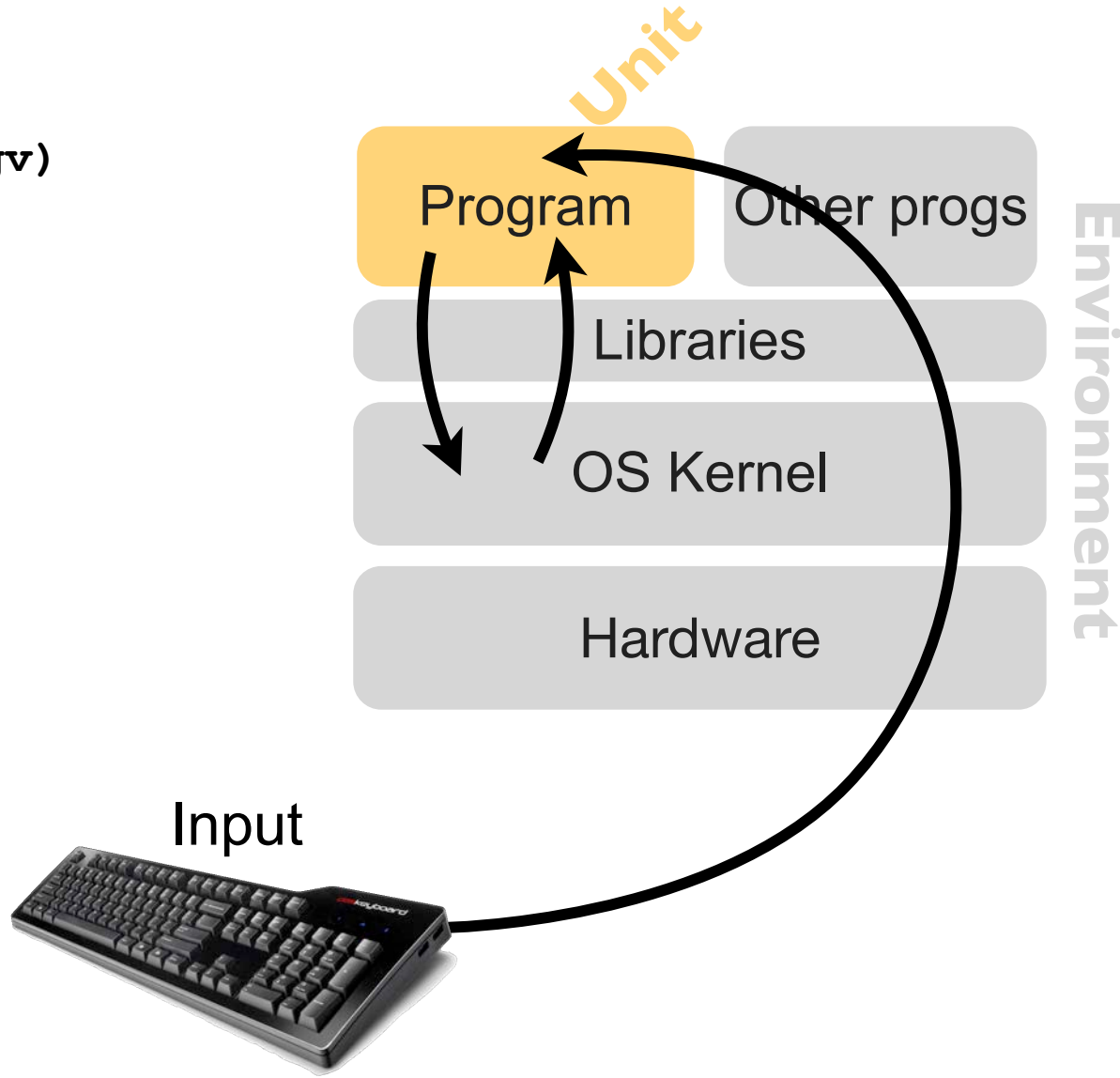
Unit



Environment

Illusion of Full-System Analysis

```
int main(argc, argv)
{
  if (argc == 0) {
     ...
  }
  p = malloc(...);
  if (p == NULL) {
     ...
  }
}
```



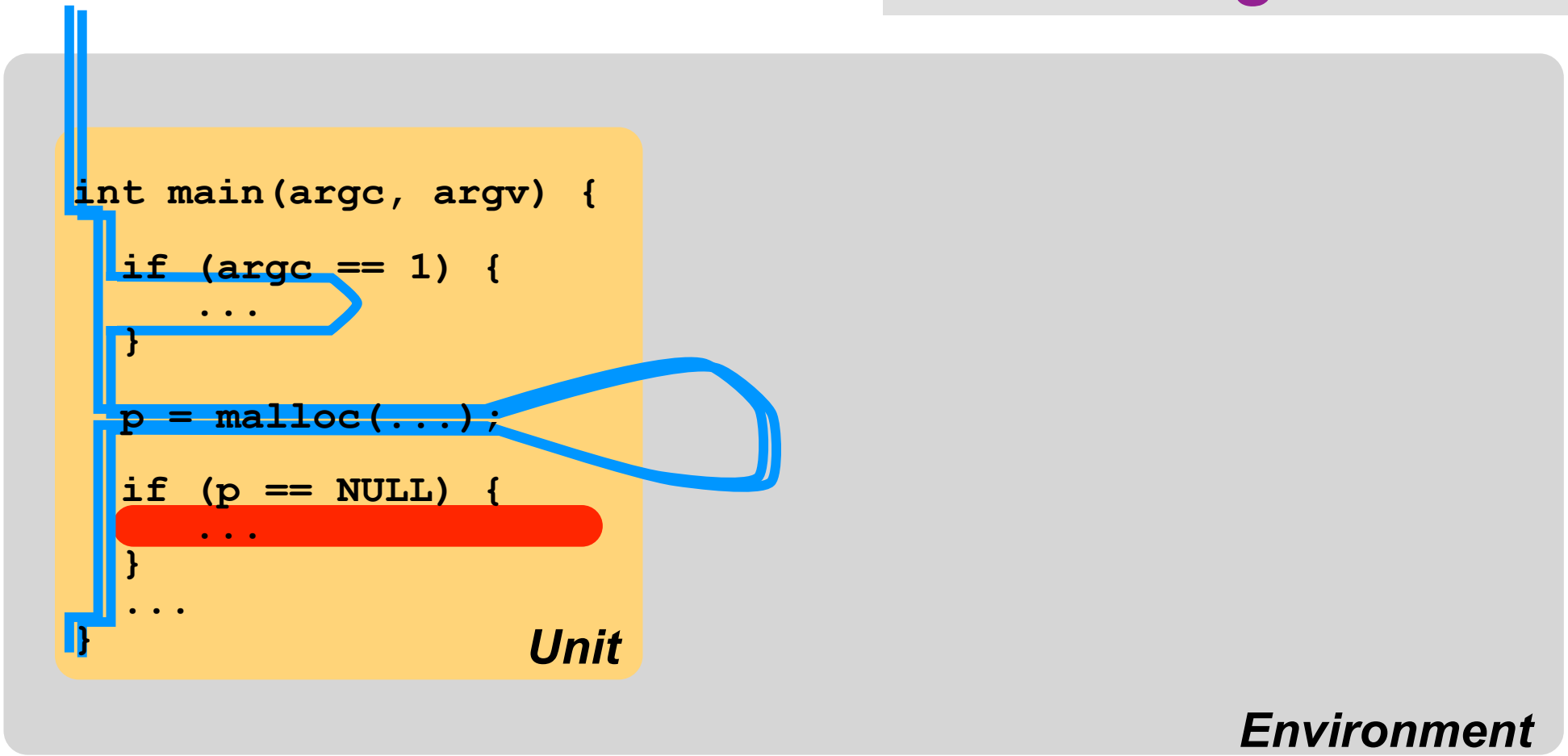
Relaxed Execution Consistency

- Allow developer to tell us which paths matter
  - *scale-up by ignoring further paths we don't care about*
  - *appropriate relaxation is analysis-specific*
  - *the illusion is automatic, relaxation is human controlled*
- Execution Consistency Model = set of paths
  - *abstract grammar/specification of which paths matter*
  - *but defined through code, not logic*

SC-UE (SC Unit-level Execution)

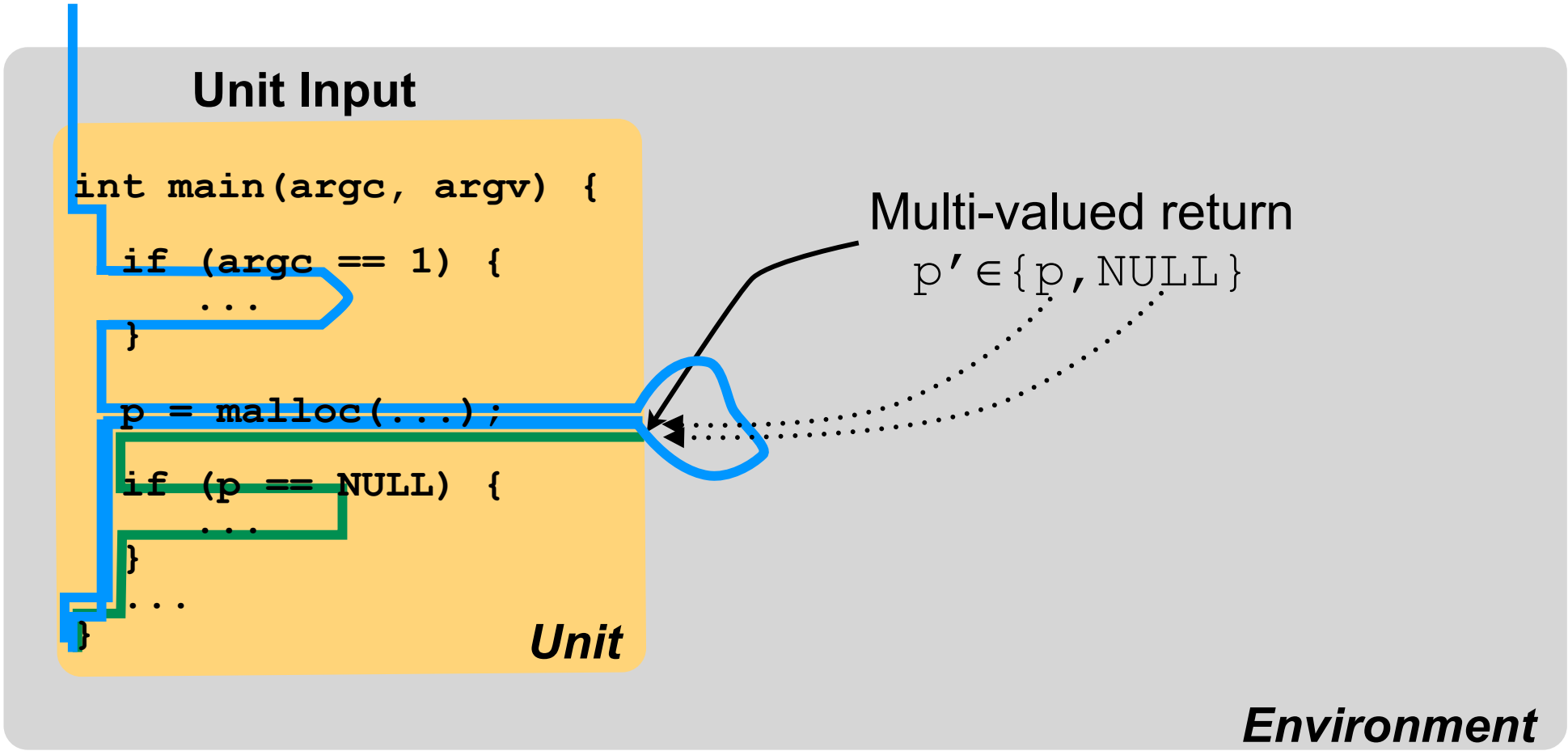
Much fewer paths

False negatives ?



Relaxed Consistency (RC)

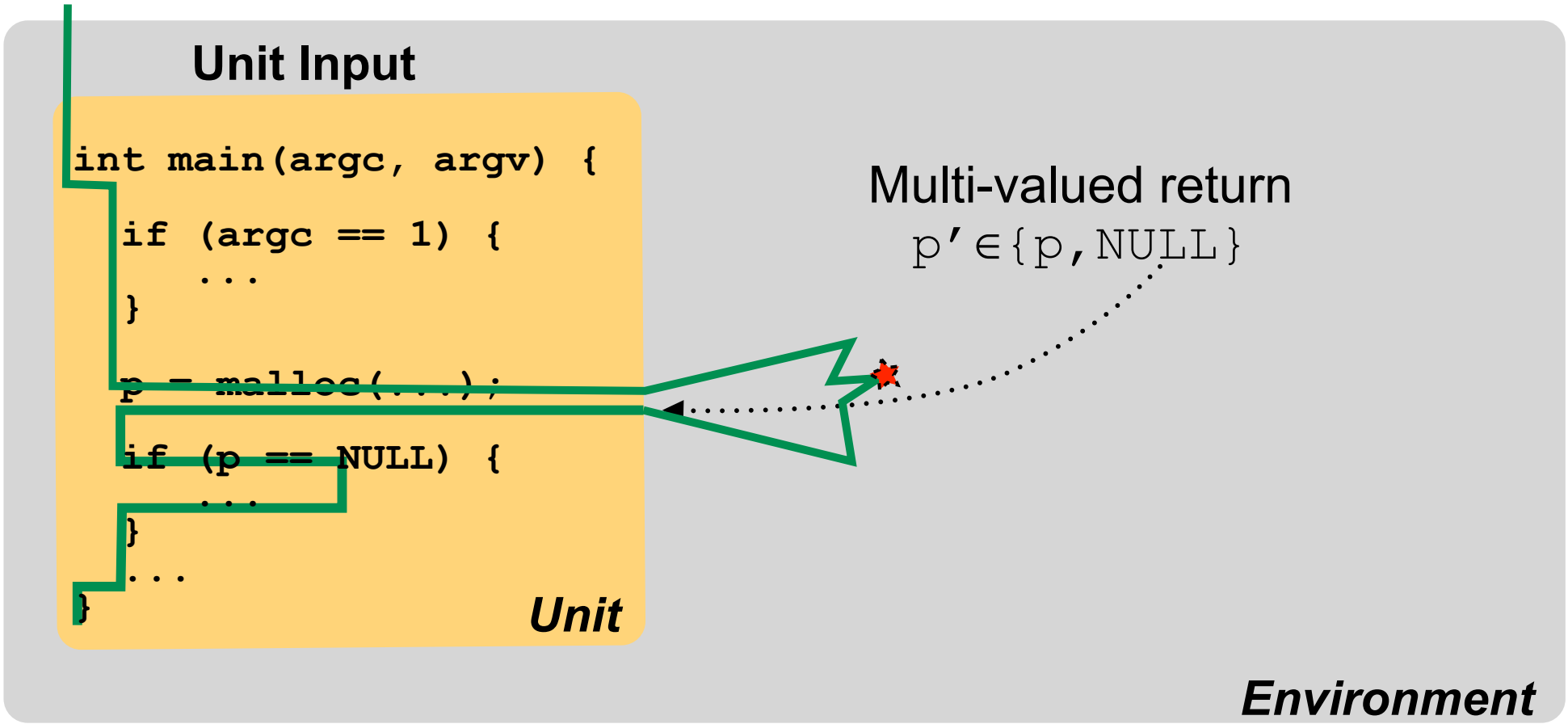
No false negatives



Relaxed Consistency (RC)

No false negatives

False positives ?



Local Consistency (LC)

Unit Input

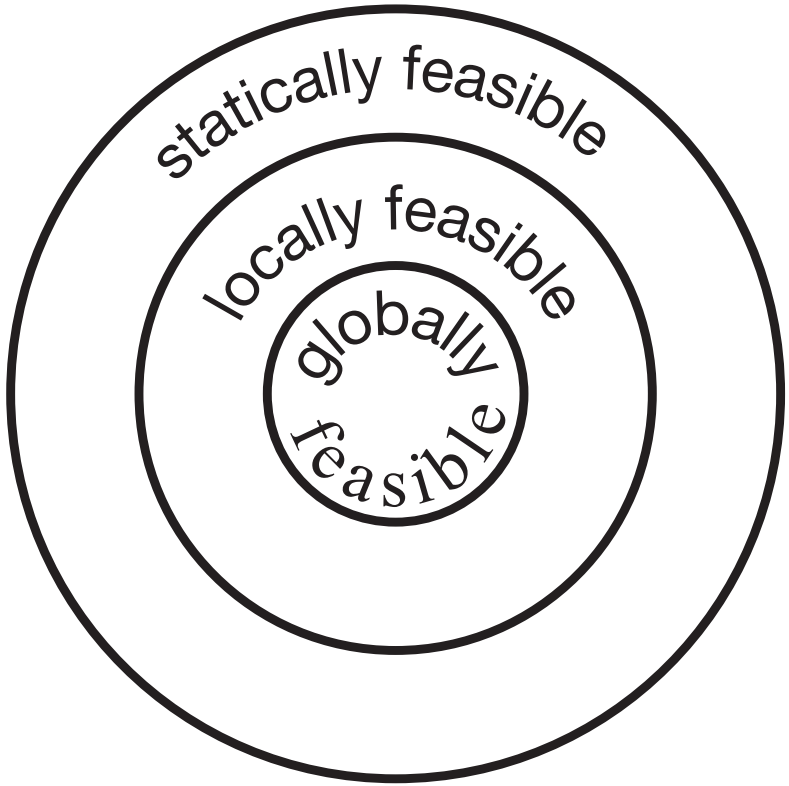
```
int main(argc, argv) {
  if (argc == 1) {
    ...
  }
  p = malloc(...);
  ...
}
```

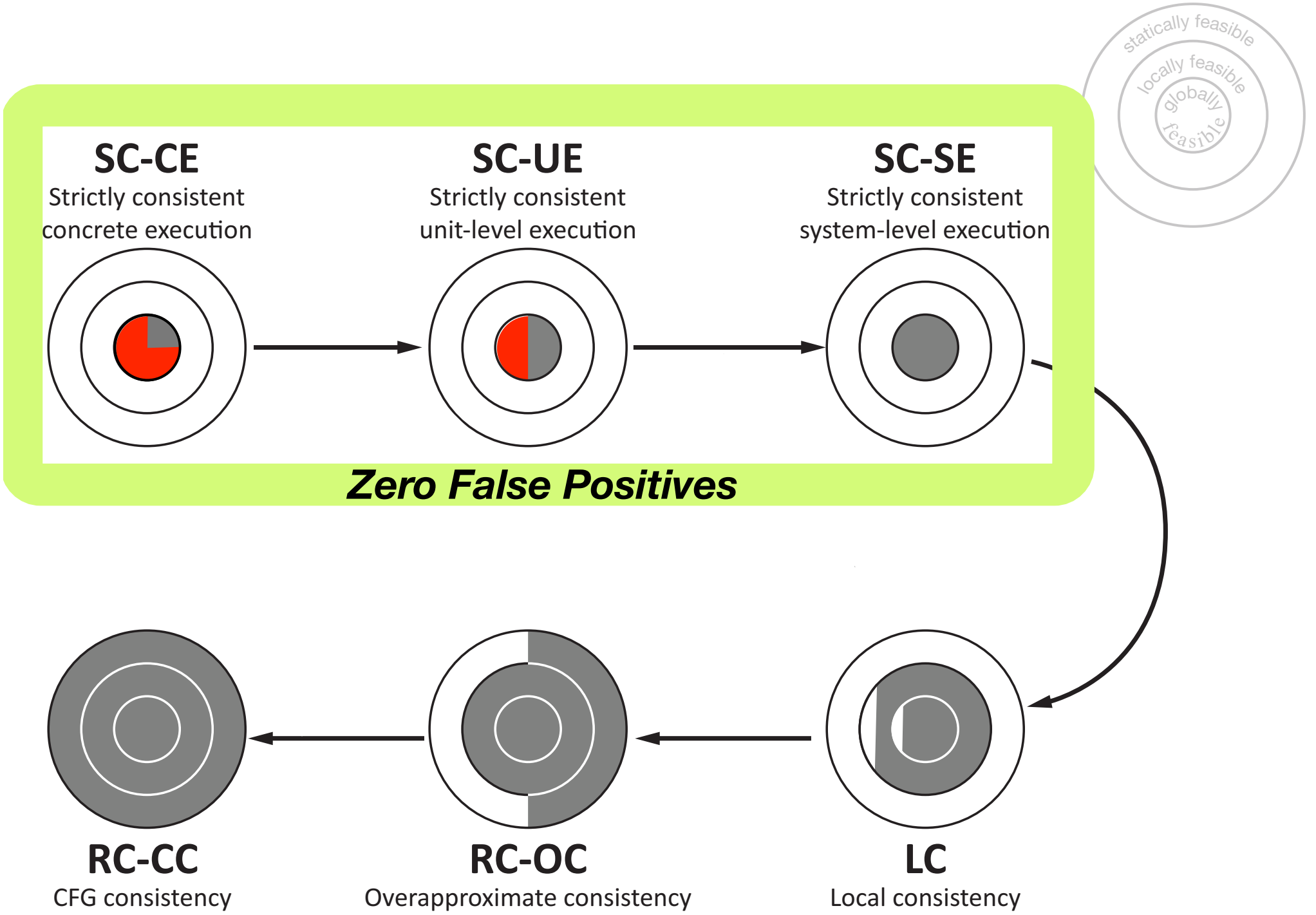
Unit

Interface annotation

`malloc() → {p,NULL}`

Environment

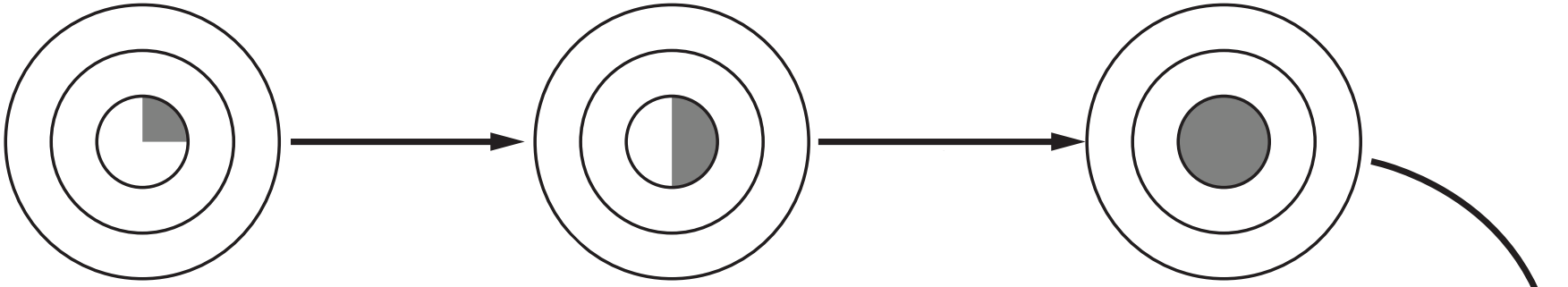

statically feasible
locally feasible
globally feasible


statically feasible
locally feasible
globally feasible
SC-CE
Strictly consistent
concrete execution
SC-UE
Strictly consistent
unit-level execution
SC-SE
Strictly consistent
system-level execution
Zero False Positives
RC-CC
CFG consistency
RC-OC
Overapproximate consistency
LC
Local consistency

SC-CE
Strictly consistent
concrete execution

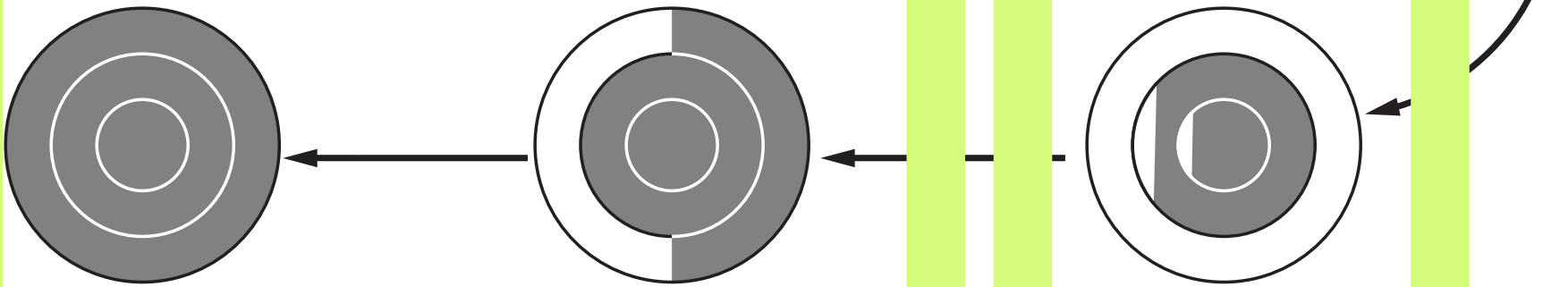
SC-UE
Strictly consistent
unit-level execution

SC-SE
Strictly consistent
system-level execution



False Positives

Zero FPs



RC-CC
CFG consistency

RC-OC
Overapproximate consistency

LC
Local consistency

Mix & Match

- ECM = specification of paths to be explored
  - *S2E underneath the covers explores the requested paths*
- Can make principled trade-offs
  - *FPs vs. FNs vs. exploration+analysis performance*
- Minimize the number of explored paths
  - *all the paths in the ECM set, but none extra*

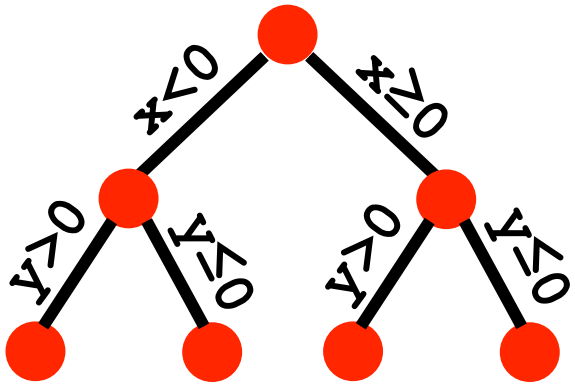
Can imperatively implement in S2E any ECM

Outline

- ~~Systems Research~~
- The S2E Platform
  - ~~*Background*~~
  - ~~*S2E: The Theory*~~
  - *S2E: The System*
- Three Use Cases

Symbolic Execution

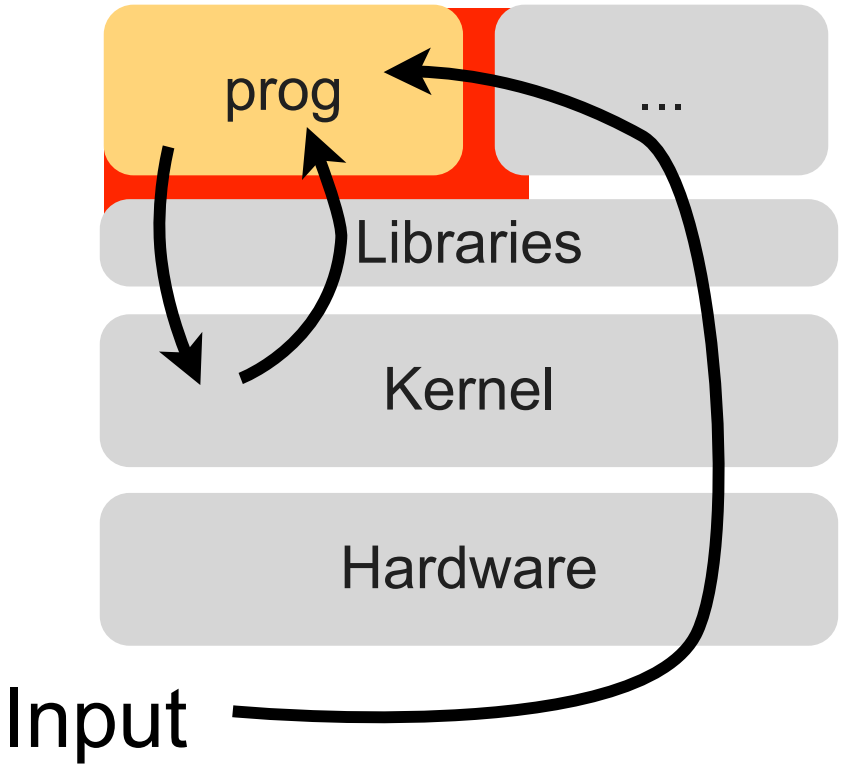
```
int func(int x, int y)
{

  if (x < 0) {
      ...
  }

  if (y > 0) {
  ...
  }

}
```



Selective Symbolic Execution

```
int main(argc, argv) {

  if (argc == 0) {
     ...
  }

  p = malloc( 0 );

  if (p == NULL) {
     ...
  }
  ...
}
```

α β 128 5



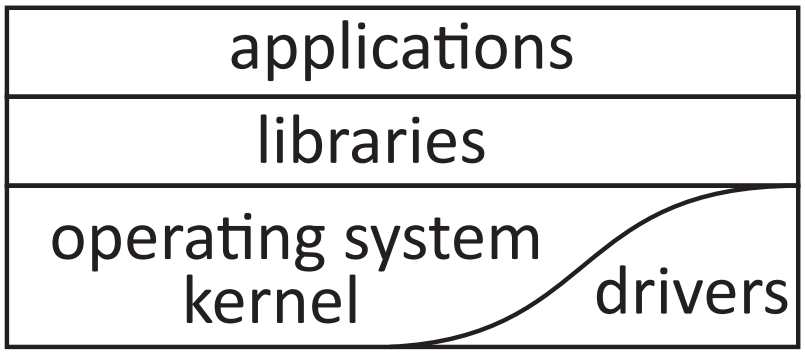
Idea #1: Virtualization

- Enable in-vivo analysis
  - *run entire system in the tool, not just the program*
- Enable true-behavior analysis
  - *system is oblivious -> behaves "naturally"*
- Analyze what actually runs
  - *i.e., x86 machine code*

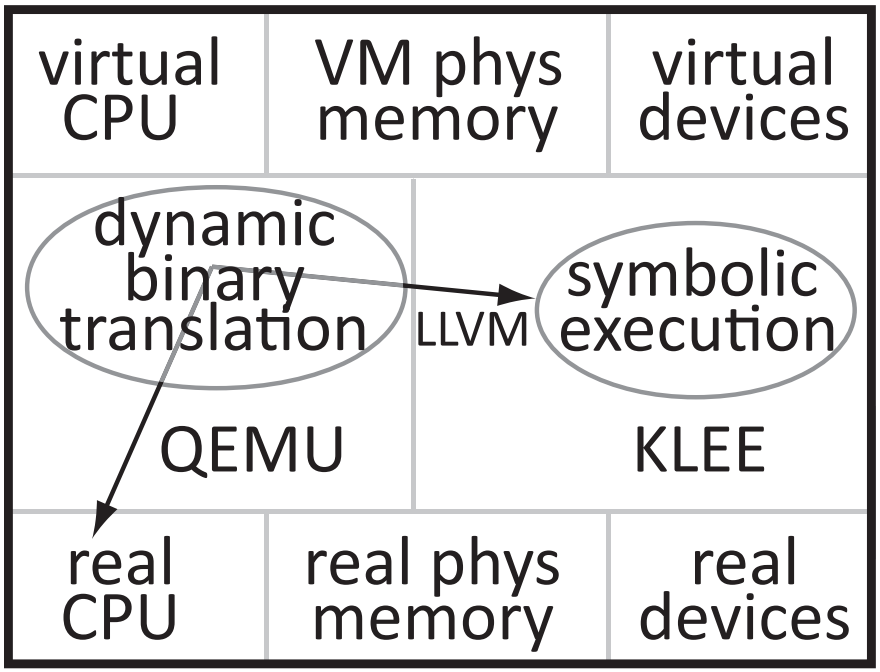
Idea #2: Dynamic Translation

- Create symbolic & concrete domains
  - *rely on DBT to alternate symbolic vs. concrete execution*
  - *do this entirely at runtime*
- Create hybrid system-state
  - *virtualized hardware shares state between domains*
  - *maintain hybrid symbolic/concrete representation*

S2E System Architecture



Runs unmodified x86 binaries (incl. proprietary/obfuscated/ encrypted binaries)

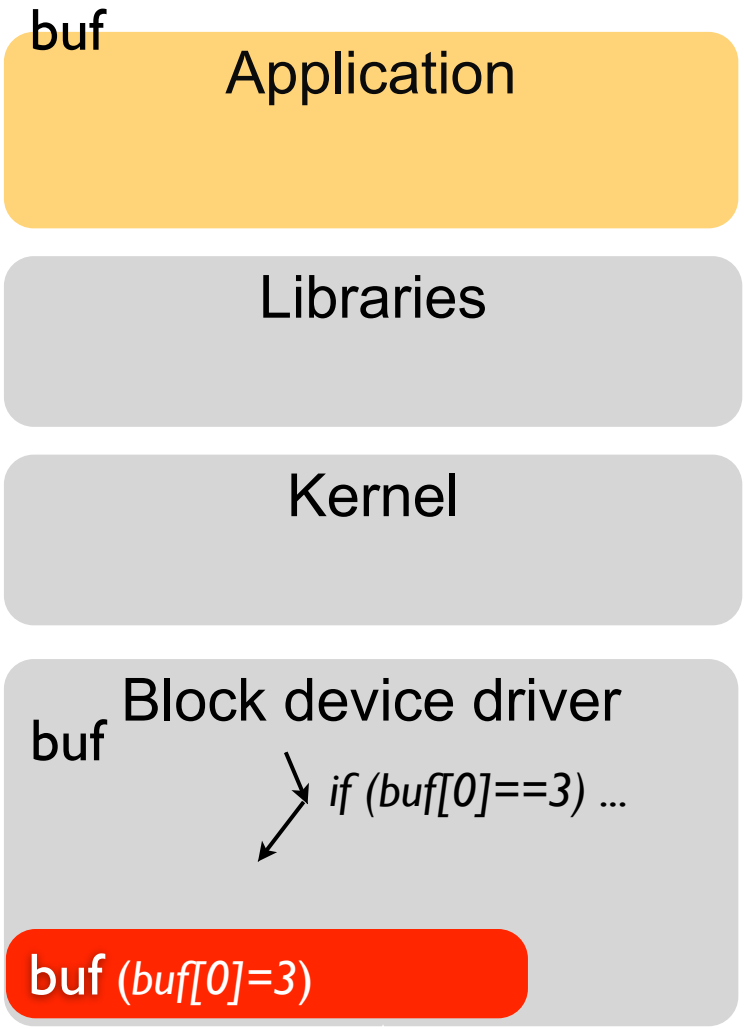


Customized virtual machine

Selection done at runtime
Most code runs “natively”

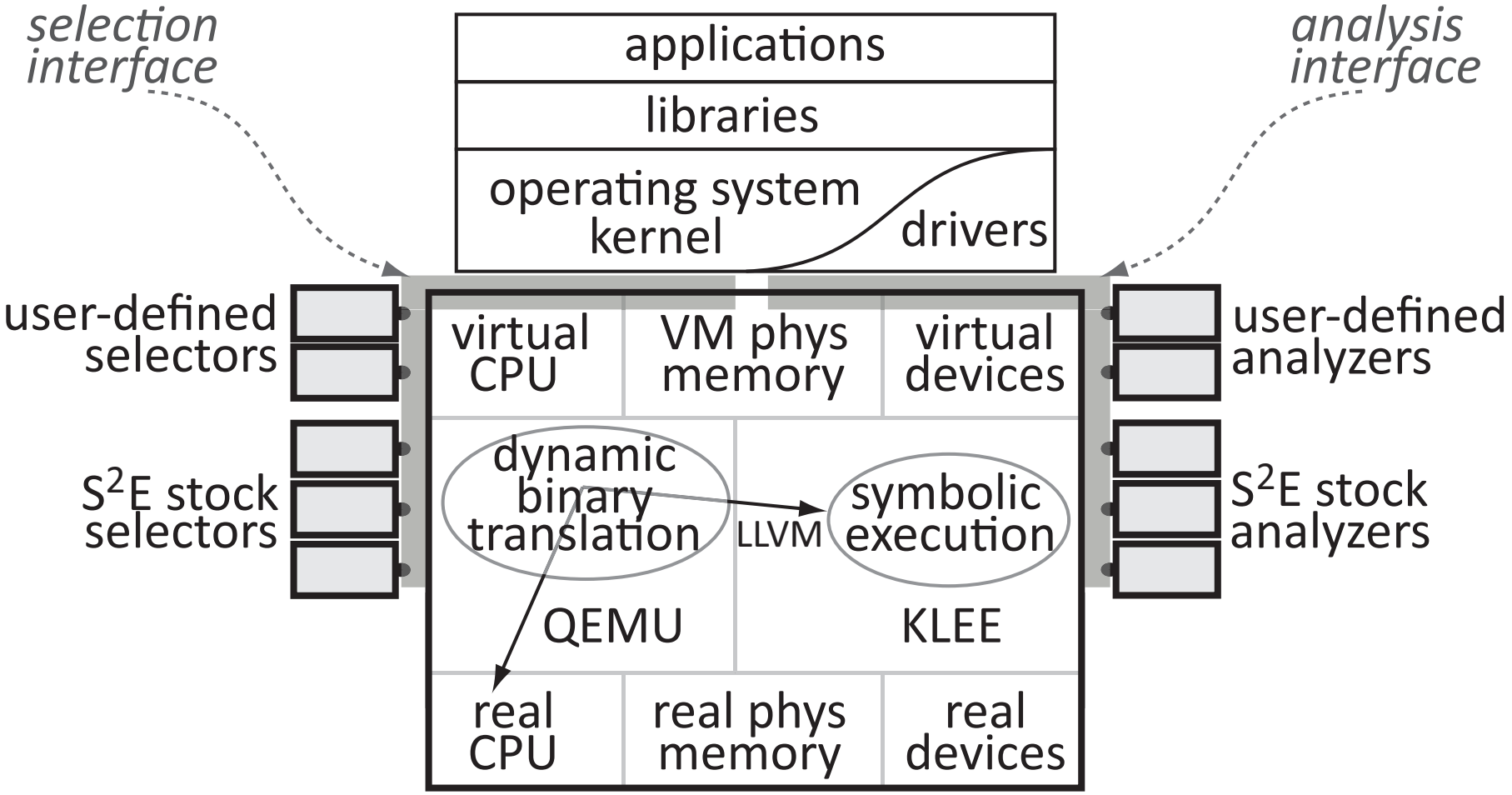
Shared concrete/symbolic state representation

Lazy + Selective Conversion



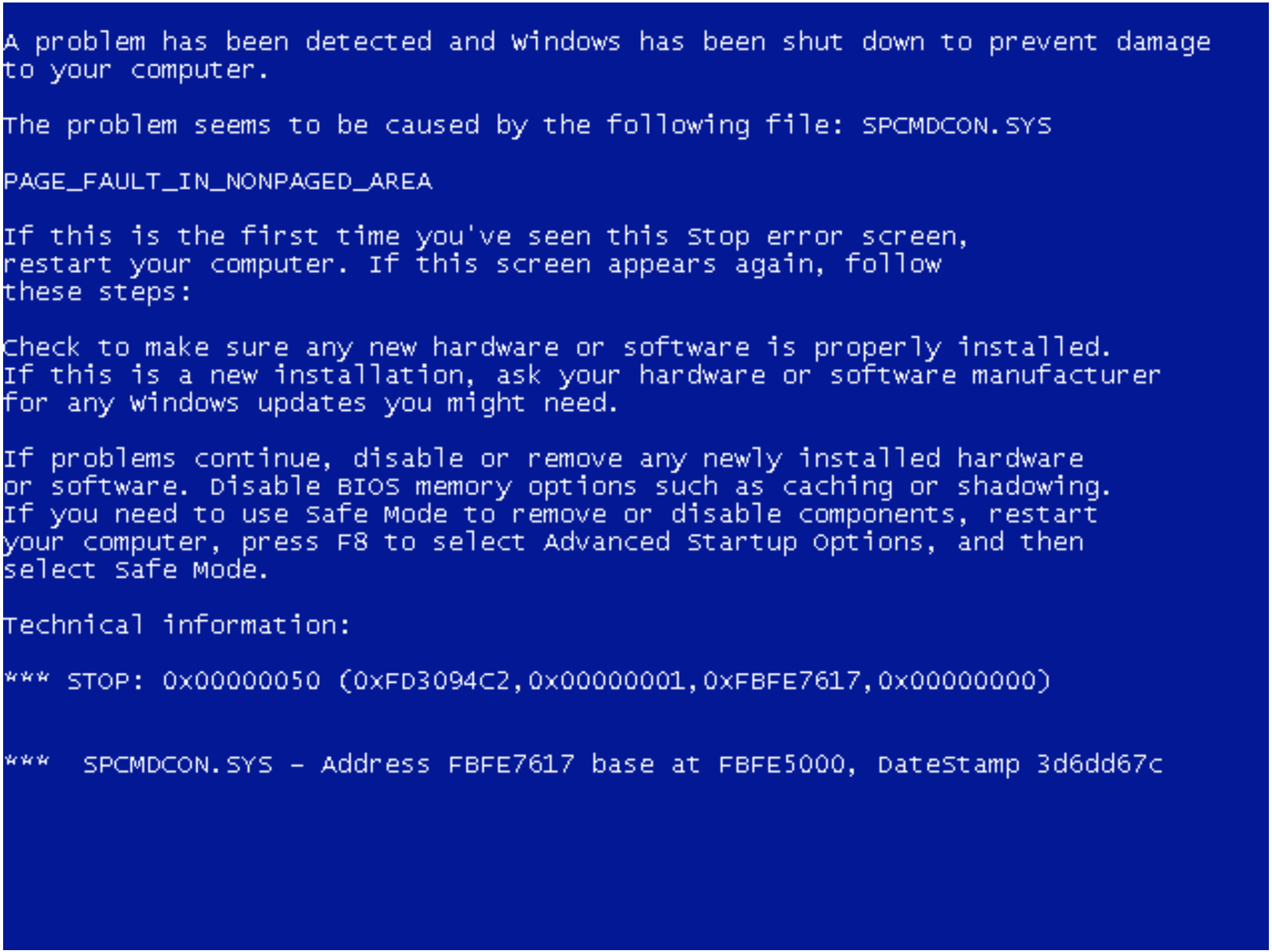
Avoids *unnecessary* concretization

S2E User's View



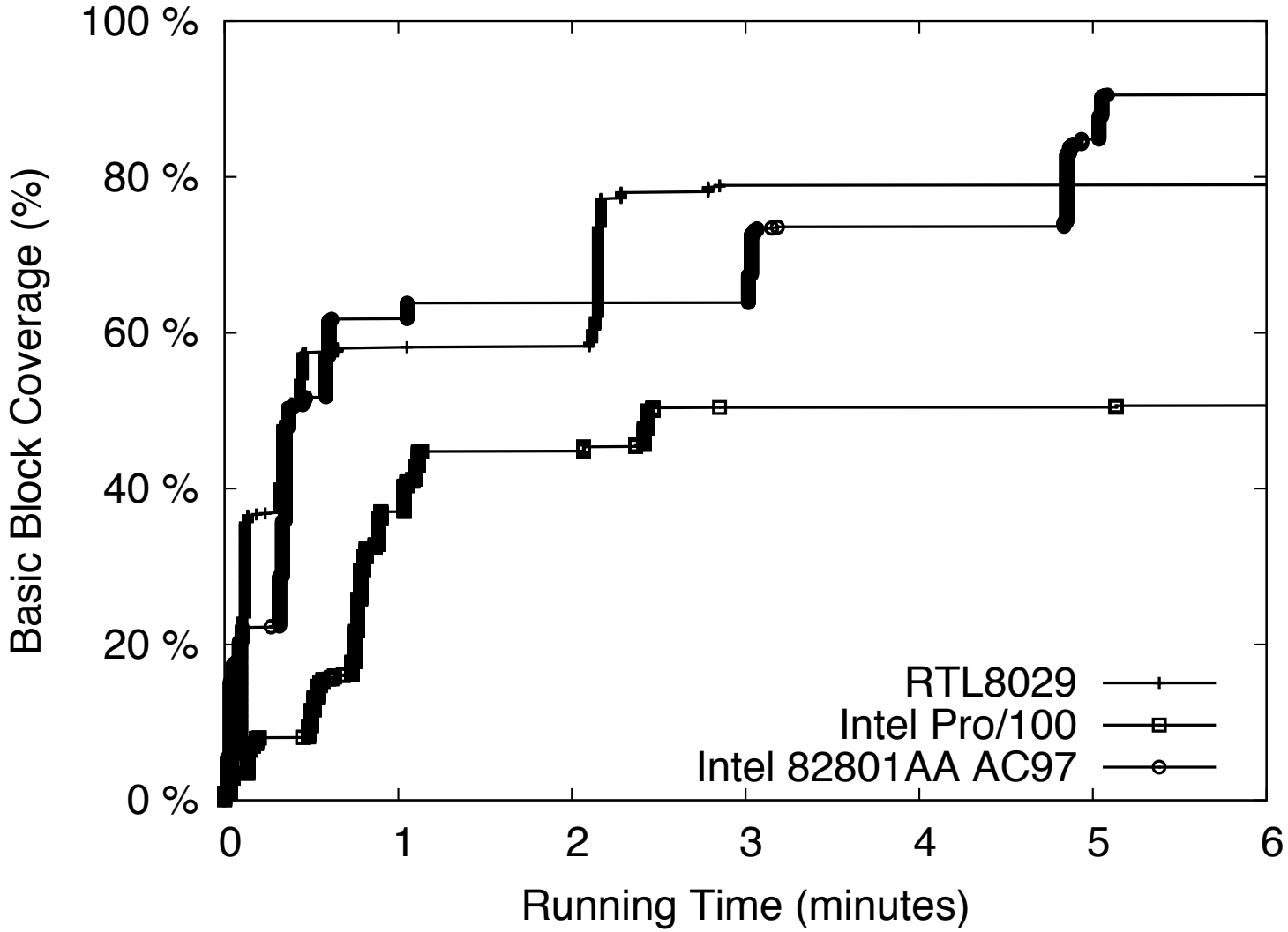
Outline

- ~~Systems Research~~
- ~~The S2E Platform~~
- Three Use Cases
  - *Testing proprietary software*
  - *Reverse engineering*
  - *Total performance profiling*


A problem has been detected and Windows has been shut down to prevent damage
to your computer.
The problem seems to be caused by the following file: SPCMDCON.SYS
PAGE_FAULT_IN_NONPAGED_AREA
If this is the first time you've seen this Stop error screen,
restart your computer. If this screen appears again, follow
these steps:
Check to make sure any new hardware or software is properly installed.
If this is a new installation, ask your hardware or software manufacturer
for any Windows updates you might need.
If problems continue, disable or remove any newly installed hardware
or software. Disable BIOS memory options such as caching or shadowing.
If you need to use Safe Mode to remove or disable components, restart
your computer, press F8 to select Advanced Startup Options, and then
select Safe Mode.
Technical information:
*** STOP: 0x00000050 (0xFD3094C2,0x00000001,0xFBFE7617,0x00000000)
*** SPCMDCON.SYS - Address FBFE7617 base at FBFE5000, DateStamp 3d6dd67c

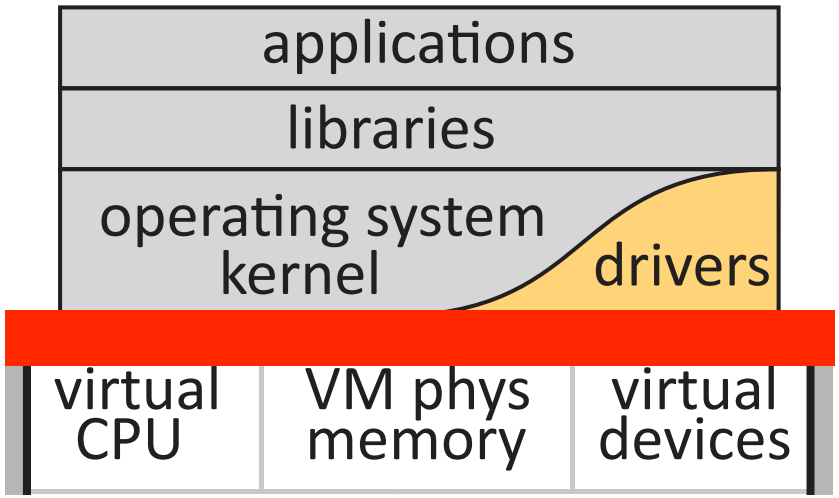
Tested Driver	Bug Type
RTL8029	Resource leak
RTL8029	Memory corruption
RTL8029	Race condition
RTL8029	Segmentation fault
RTL8029	Segmentation fault
AMD PCNet	Resource leak
AMD PCNet	Resource leak
Ensoniq AudioPCI	Segmentation fault
Ensoniq AudioPCI	Segmentation fault
Ensoniq AudioPCI	Race condition
Ensoniq AudioPCI	Race condition
Intel Pro/1000	Memory leak
Intel Pro/100 (DDK)	Kernel crash
Intel 82801AA AC97	Race condition

Analysis Time < 20 Minutes



Symbolic Hardware

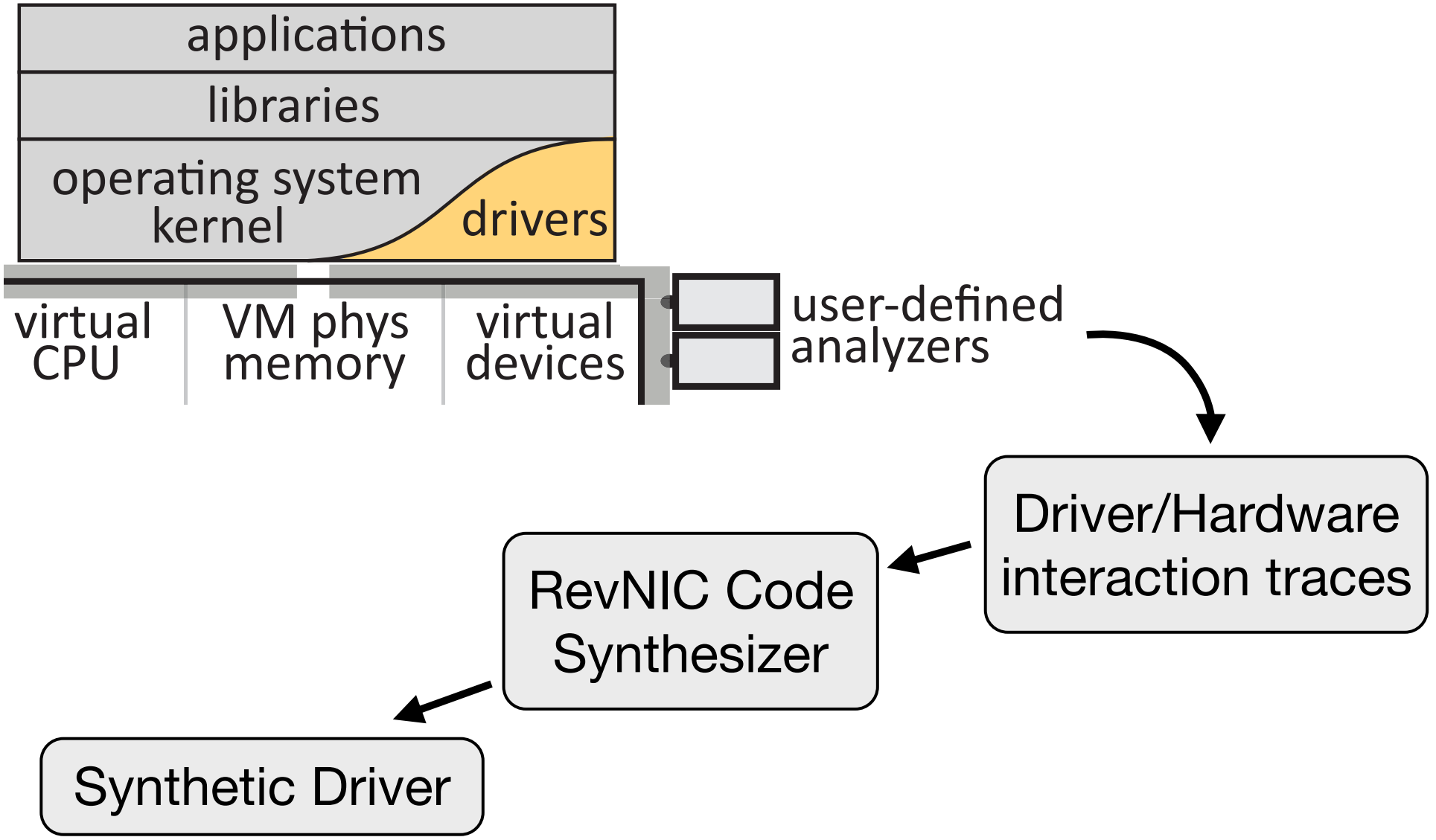
- Symbolic HW inputs, symbolic interrupts, etc.
- Test without having the real hardware
- Test for bad hardware behaviors



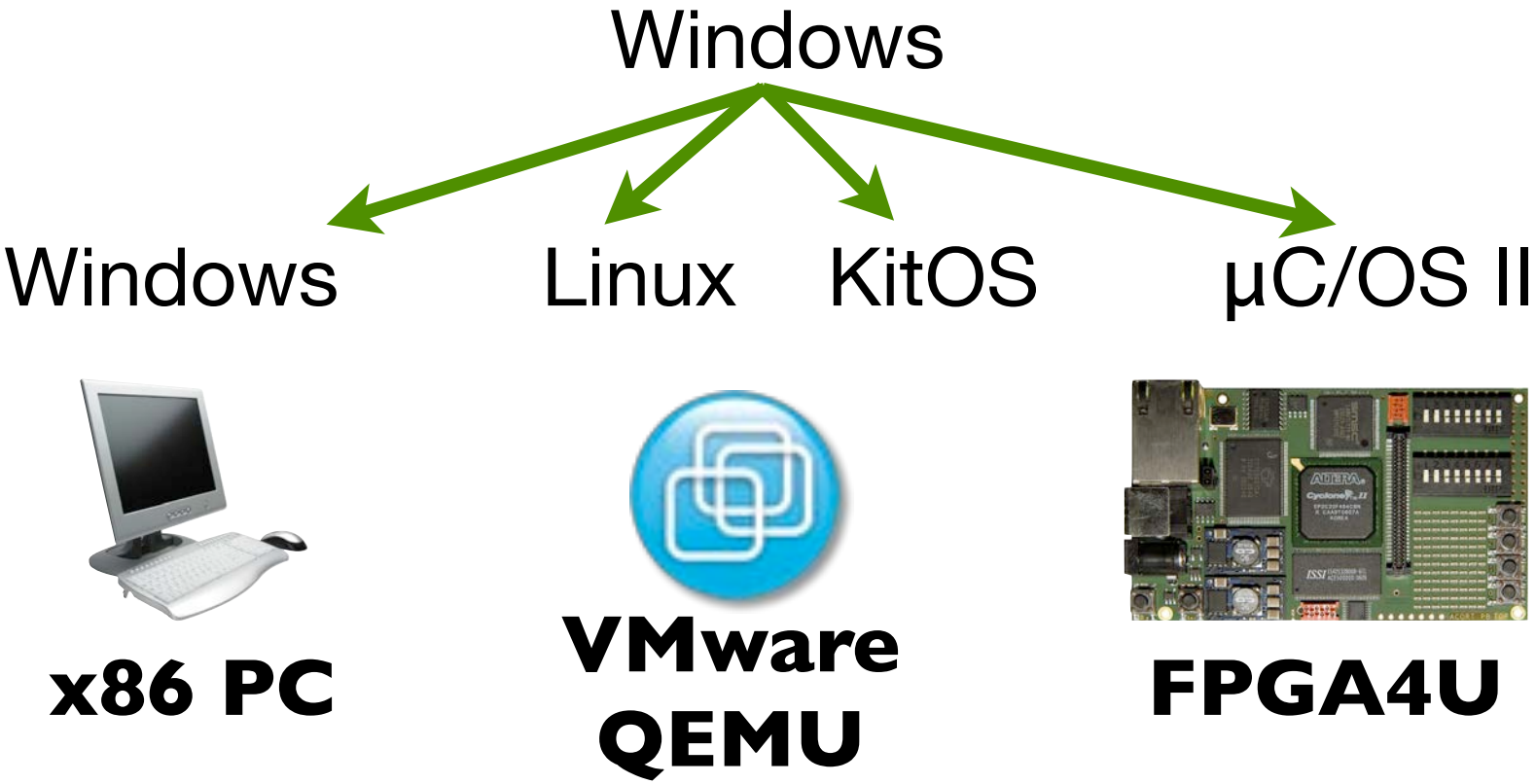
Outline

- Systems Research
- The S2E Platform
- Three Use Cases
  - *Testing proprietary software*
  - *Reverse engineering*
  - *Total performance profiling*

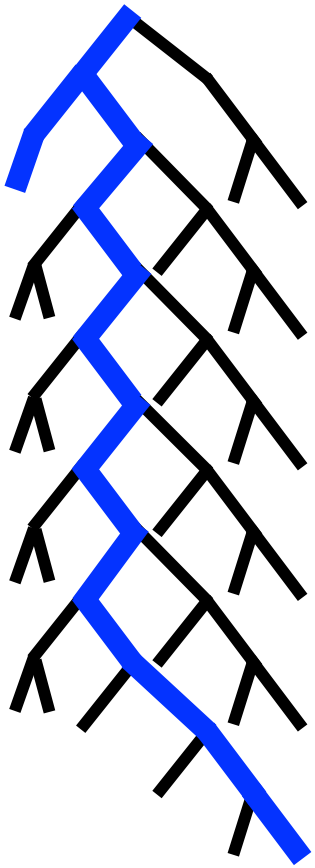
RevNIC+ Reverse Engineering



Automated Porting



PROFs: Total Performance Profiling



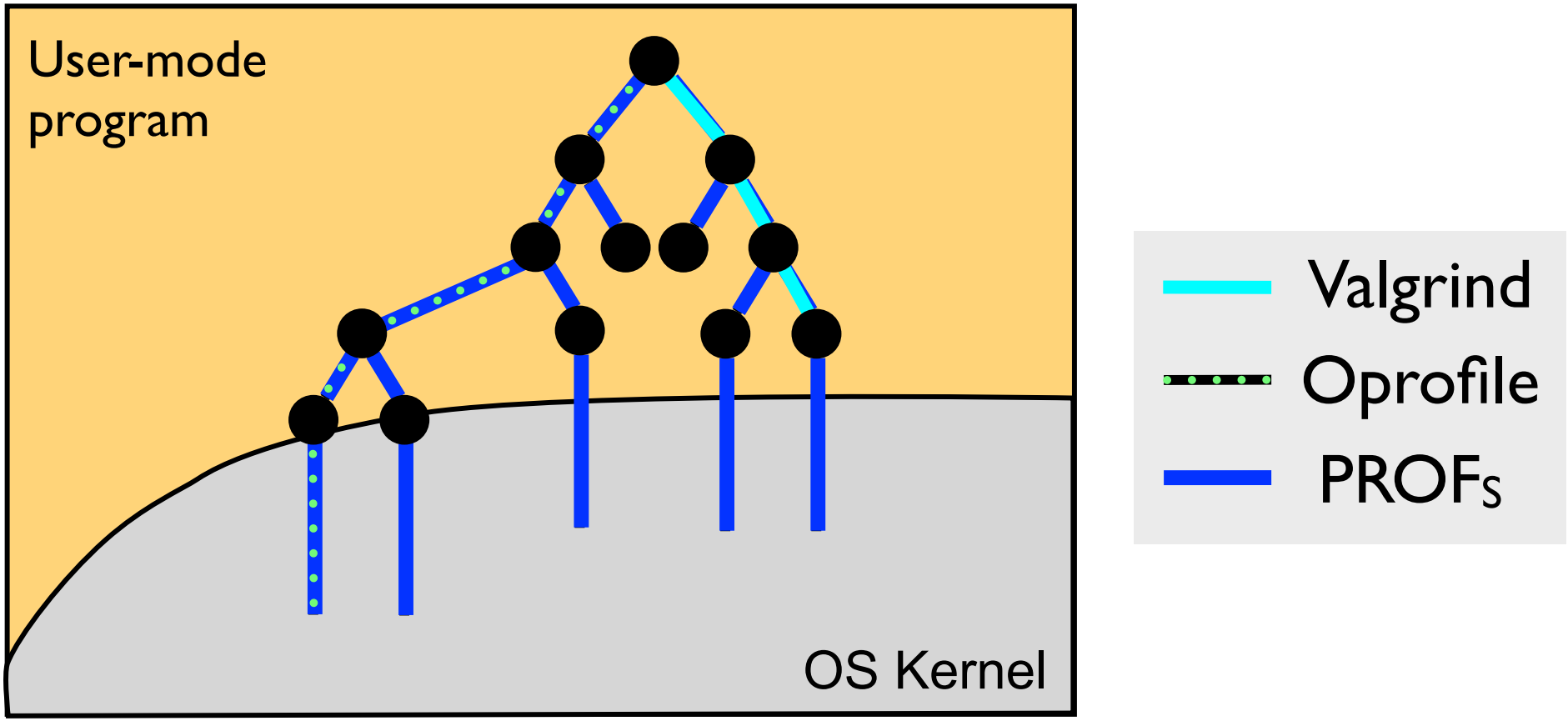
1,645 instructions

`ping`

129,086 instructions

- Apache URL parser
- Microsoft IIS SSL module
- Lua language interpreter
- Various utilities

Multi-Path In-Vivo Profiling



Productivity Results

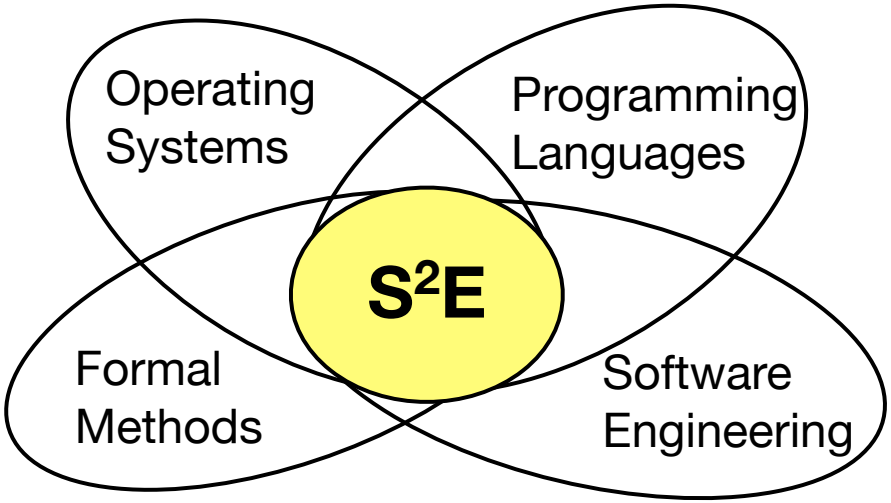
PROF$_S$
20 person-hours
767 lines of code

RevNIC$^+$
40 person-hours*
580 lines of code

DDT$^+$
38 person-hours
720 lines of code

S2E Platform
> 100,000 lines of code
47,000 lines of new code

Summary



- Approach
  - *powerful analysis -> deeper understanding -> more rigorous composition -> formal verification?*
- Borrow ideas to solve systems problems
  - *systems research is interdisciplinary by definition*

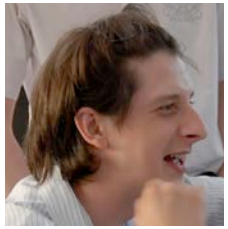
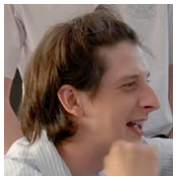
http://s2e.epfl.ch

Ready-to-play VM, demos, tutorials, source code, documentation

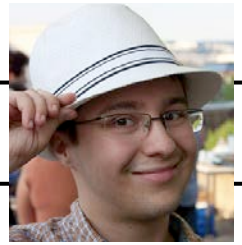
Outline

- ~~Systems Research~~
- ~~The S2E Platform~~
- ~~Three Use Cases~~
  - ~~*Testing proprietary software*~~
  - ~~*Reverse engineering*~~
  - ~~*Total performance profiling*~~

Tools & Systems

Automated Testing	Automated Debugging	Automated Correcting	Scalable Certification
DDT Test proprietary code 	**ESD** Execution synthesis 	**Dimmunix** Deadlock immunity 	**iProve** End-user verifiability 
LFI Test recovery code 	**Portend** Date race classifier 	**RevNIC** Reverse engineering 	**iQA** Rating & certification  
ConfErr Human error testing 			

Core Techs



Cloud9 - Cluster-based parallel symbolic execution

S²E - Selective symbolic execution of full software stacks