S²E

A Platform for In-Vivo Multi-Path Analysis of Software Systems

Vitaly Chipounov, Volodymyr Kuznetsov,
George Candea

School of Computer & Communication Sciences

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Bug Finding

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$ ./prog
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Segmentation fault
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Segmentation fault


$ valgrind ./prog p1
Invalid read of size 1
main (prog.c:10)
```

Performance Profiling

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  for(i = 0; i < m.w; i++)
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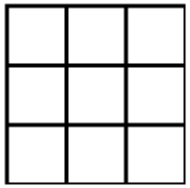

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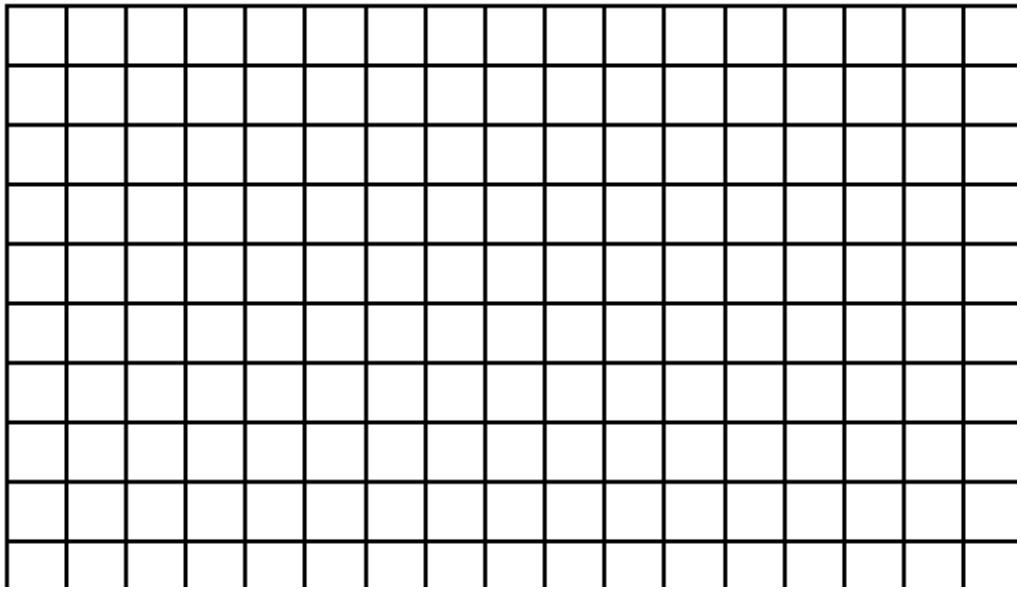

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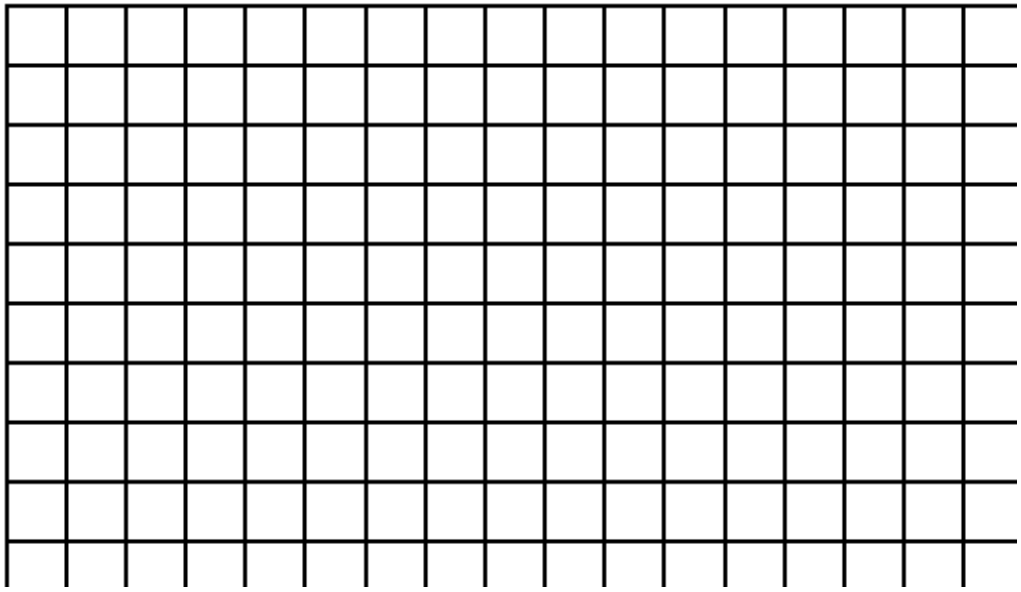

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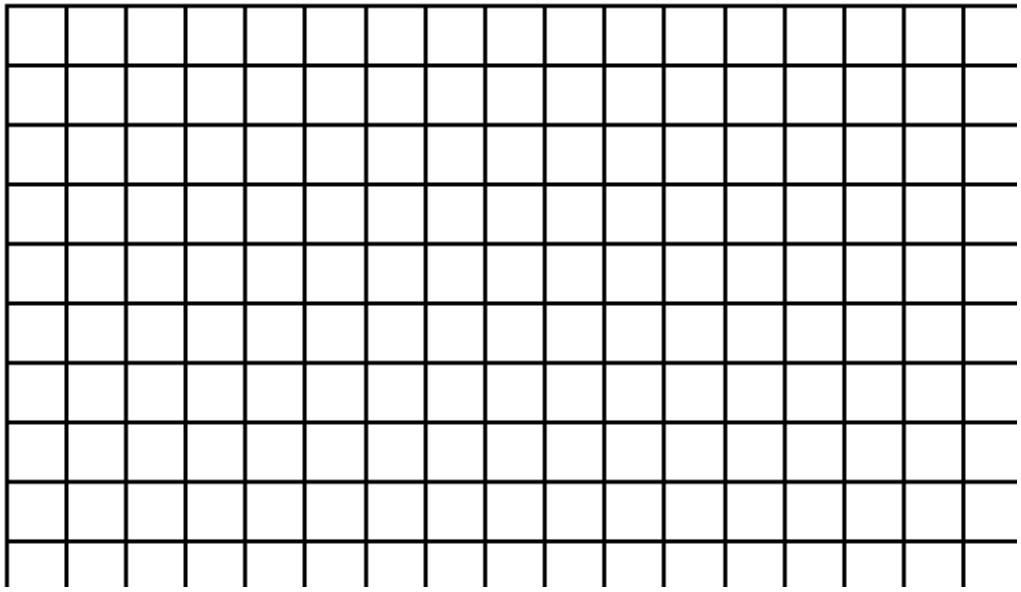

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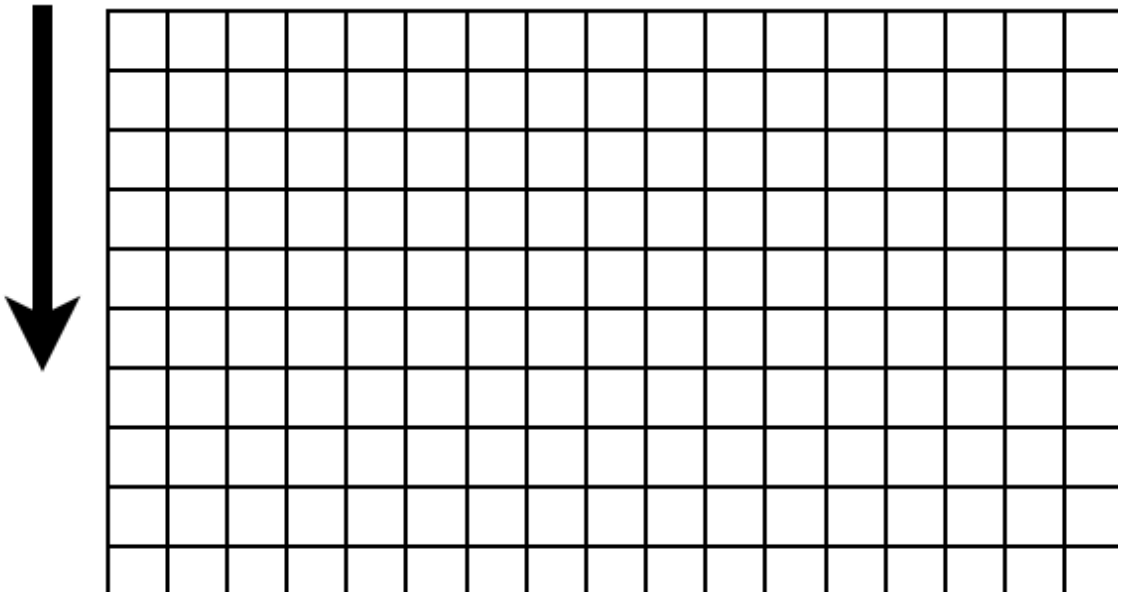

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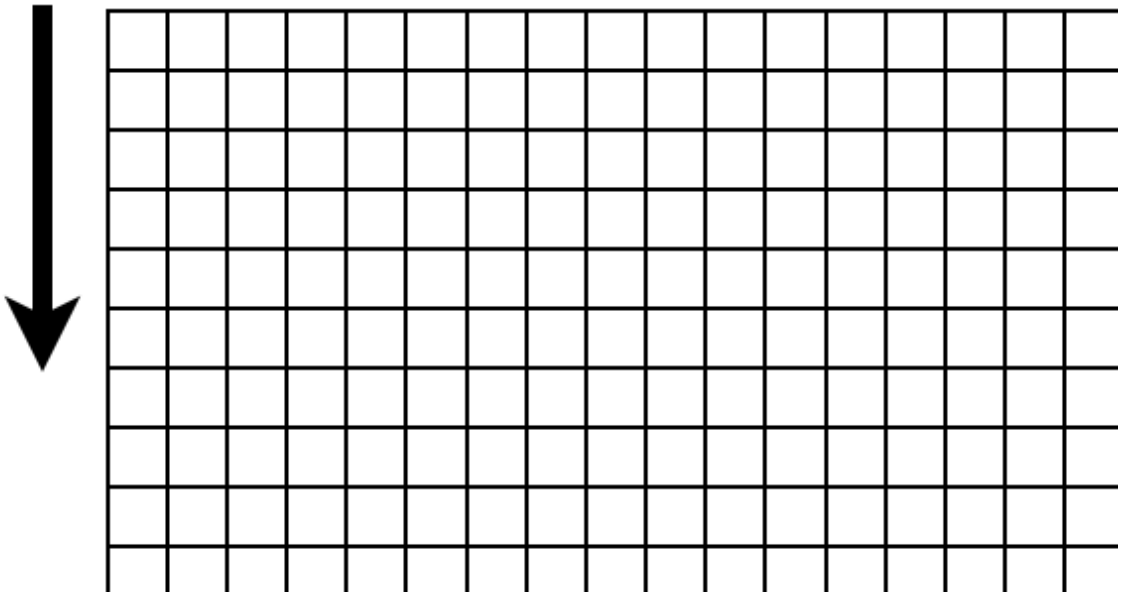

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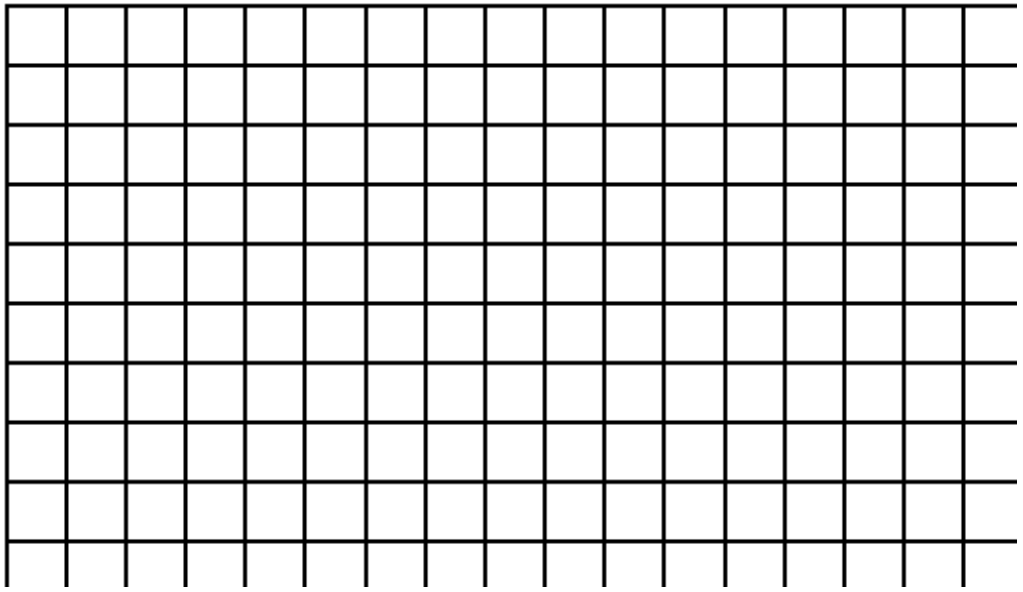

Analyses

- Bug finding
- Performance profiling
- Verification/Certification
- Security analysis
- ...

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Check properties on execution paths

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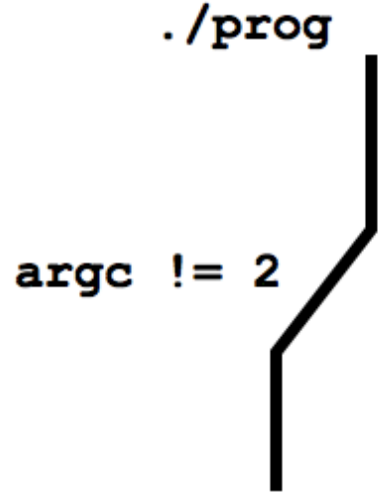

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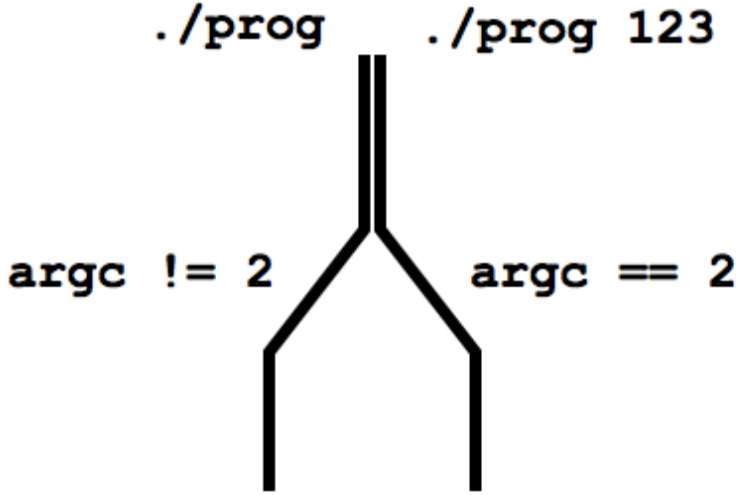

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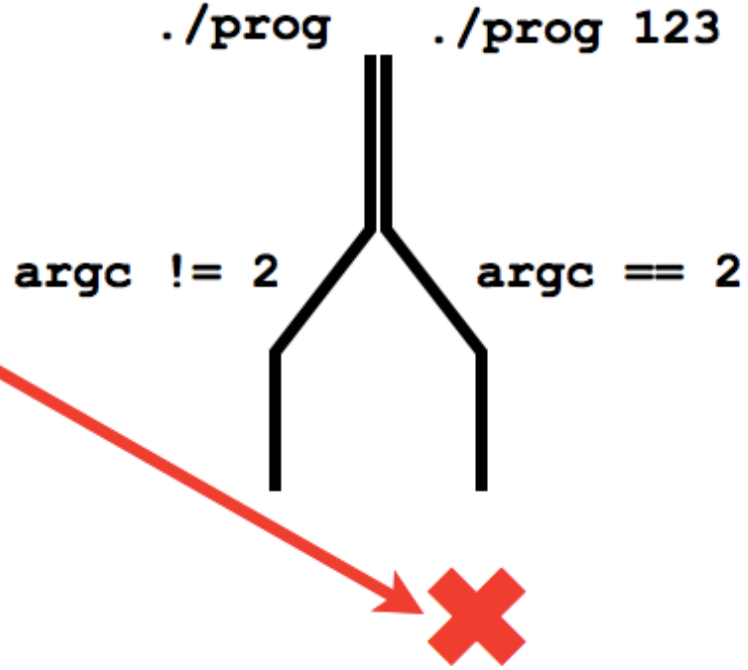

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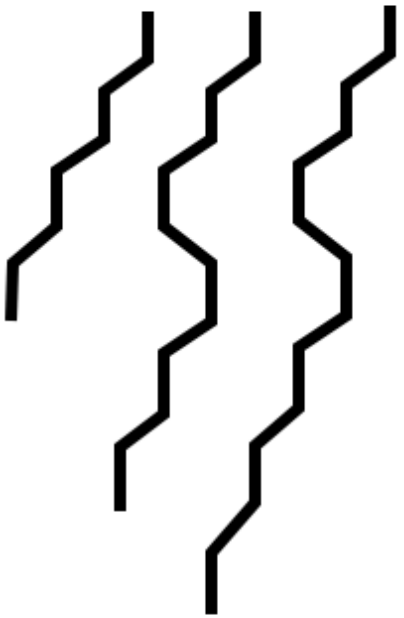

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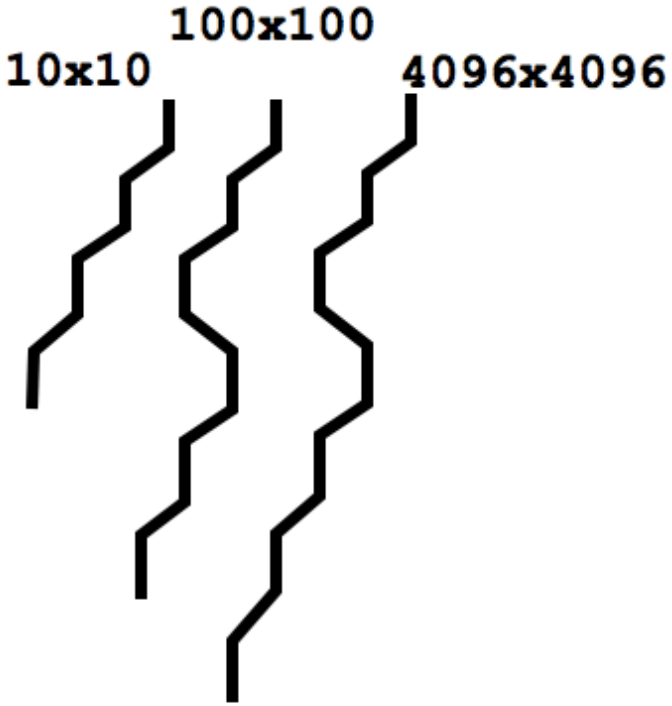

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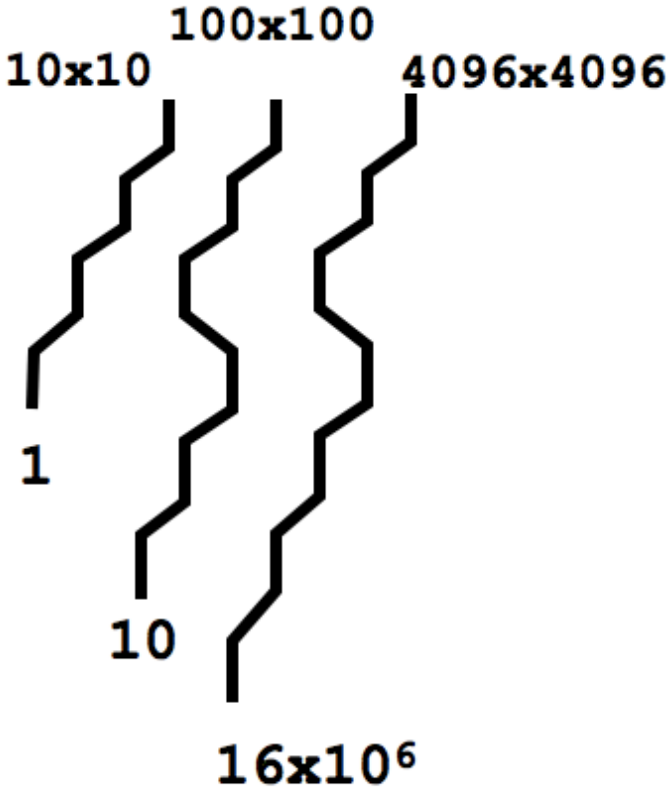

Cache misses

Systematic Path Enumeration

- Automatically finding the right paths
  To detect bugs
  To expose performance issues
  To ...

In-Vivo Multi-Path Analysis

Analyze a *living* system, for maximum realism

http://www.wtcc.wur.nl/NR/rdonlyres/E8C658AD-8303-41D9-A141-E5413DB9E3BD/41107/invitro.jpg

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Challenge

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$2^{\text{system size}}$ paths

Today's Approaches

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Analyze only some of the paths
Introduces false negatives (FNs)

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Analyze only some of the paths
Introduces false negatives (FNs)

Abstract away parts of the paths
Introduces false positives (FPs)

Outline

- Theory
  Execution consistency models
- System
  S²E: Platform for in-vivo multi-path analysis
- Results
  Using S²E in practice

http://s2e.epfl.ch

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- Remember memory consistency models ?

Consistency Models in S2E

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int main(argc, argv) {

  if (argc == 0) {
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prog

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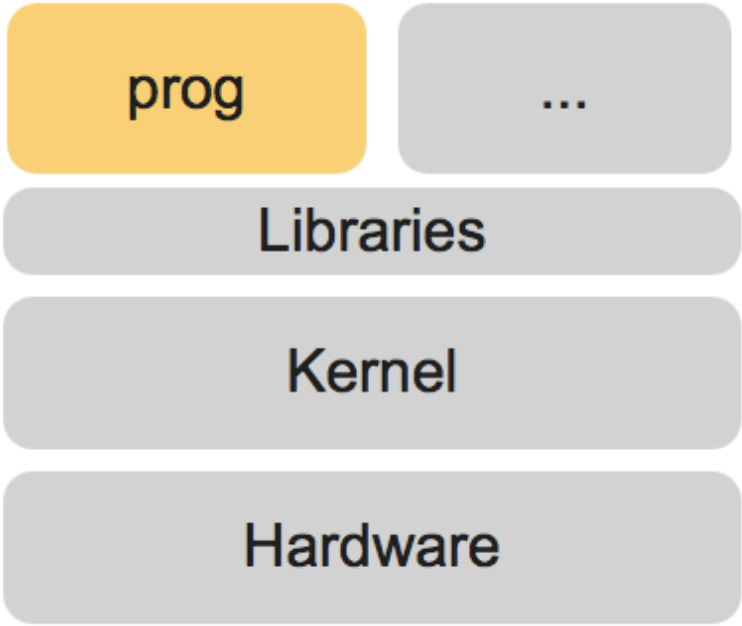

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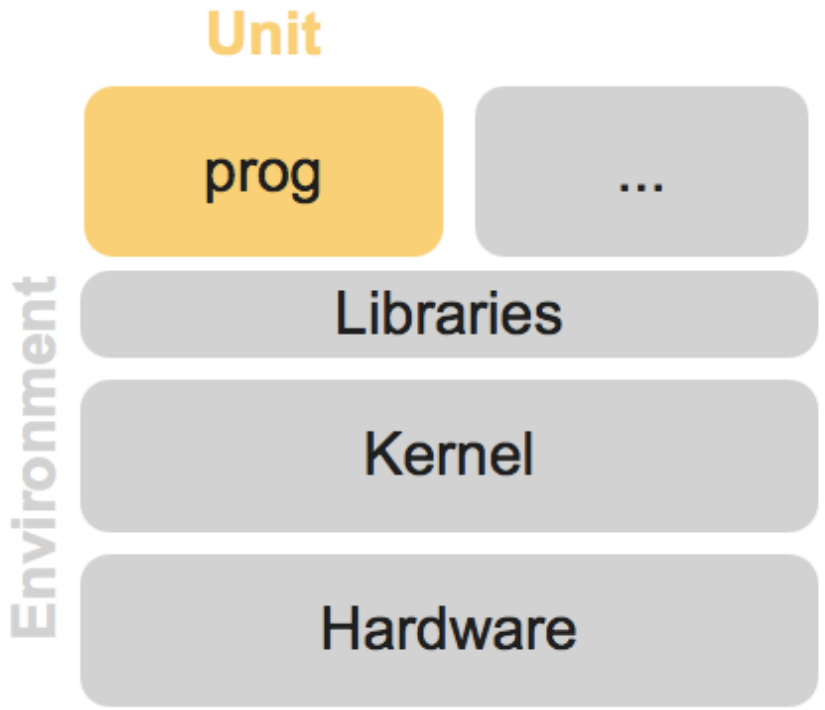

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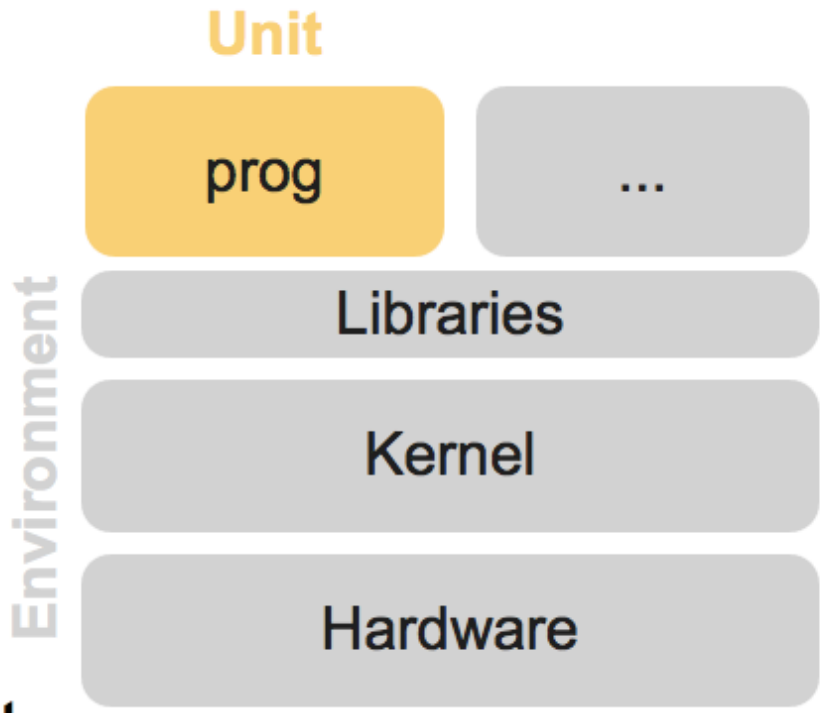

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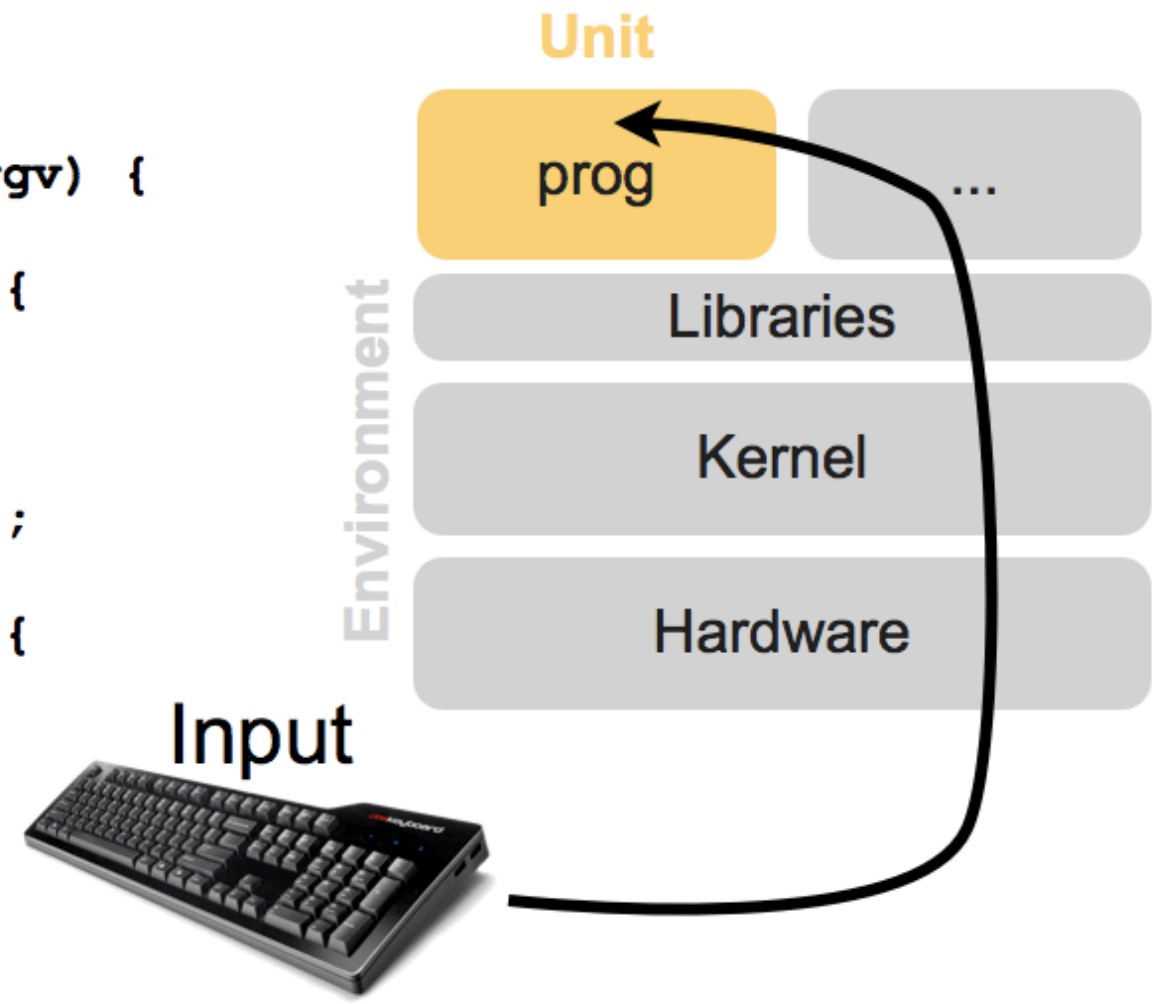

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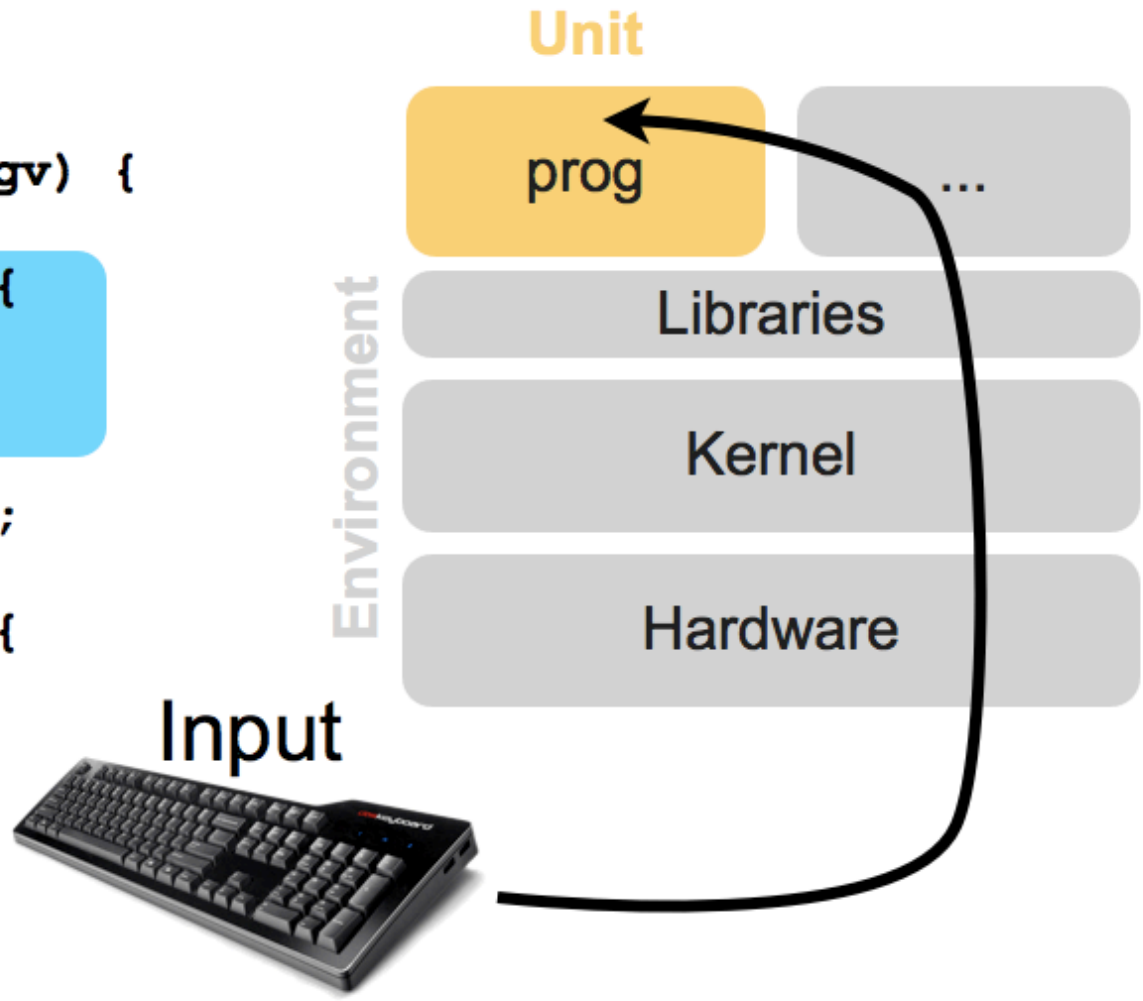

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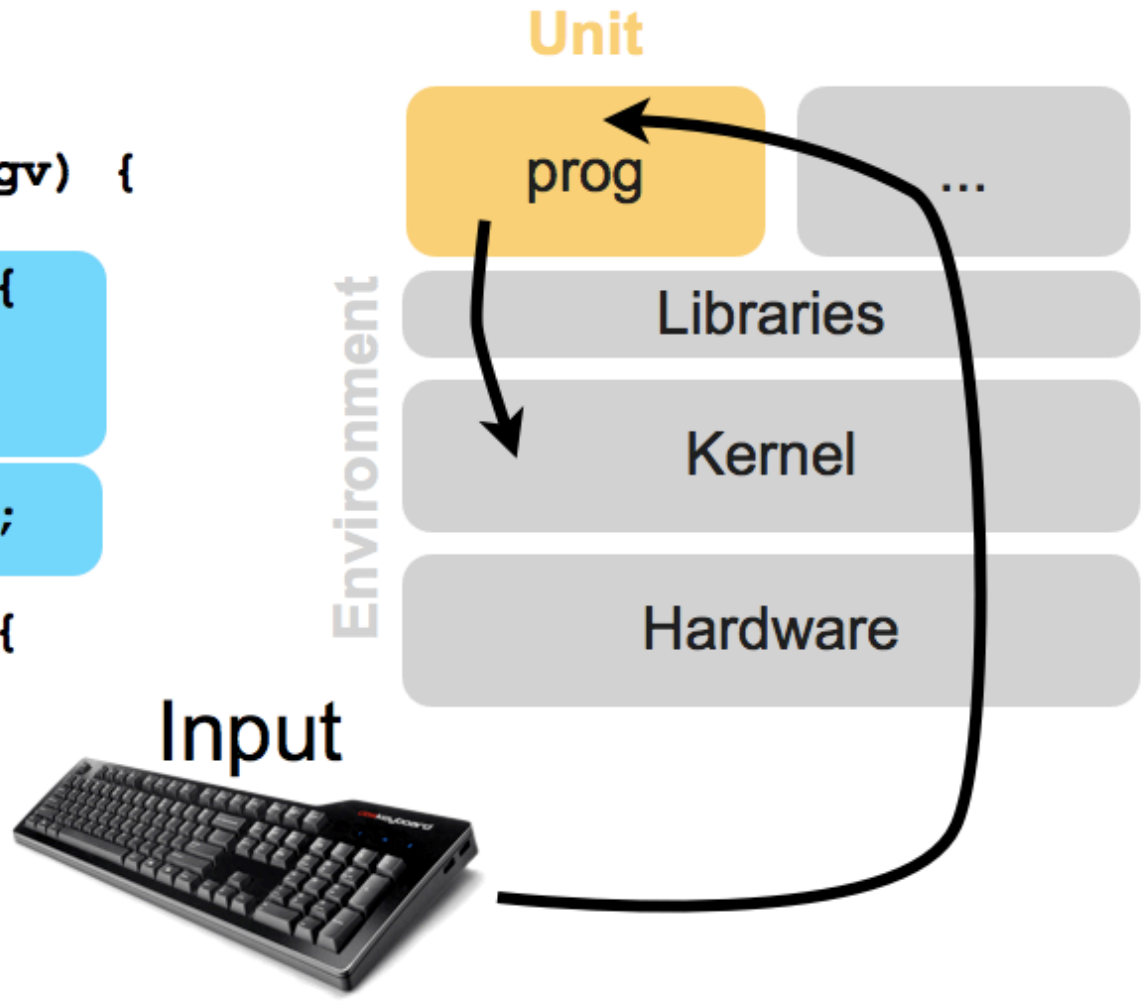

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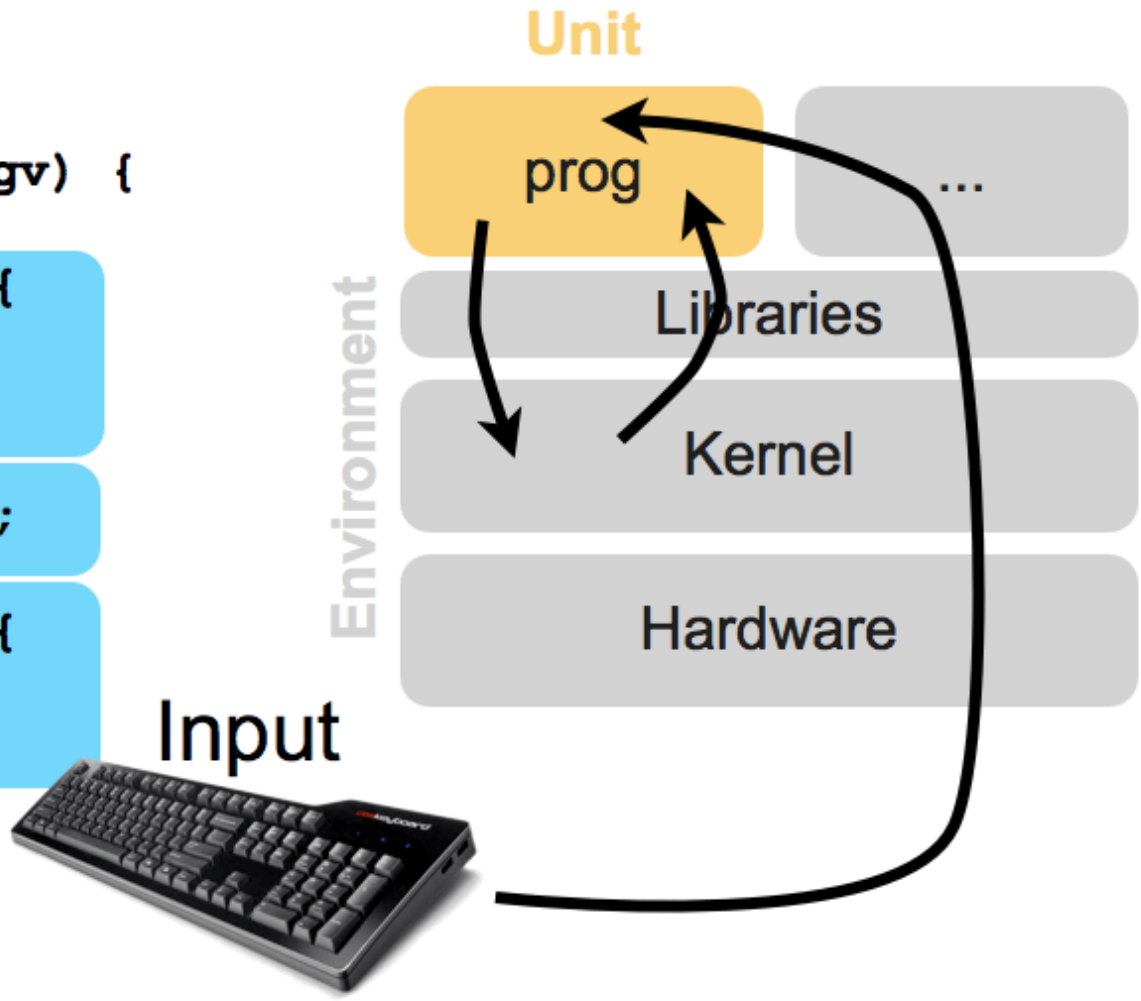


SC-SE

Strictly Consistent *System*-Level Execution

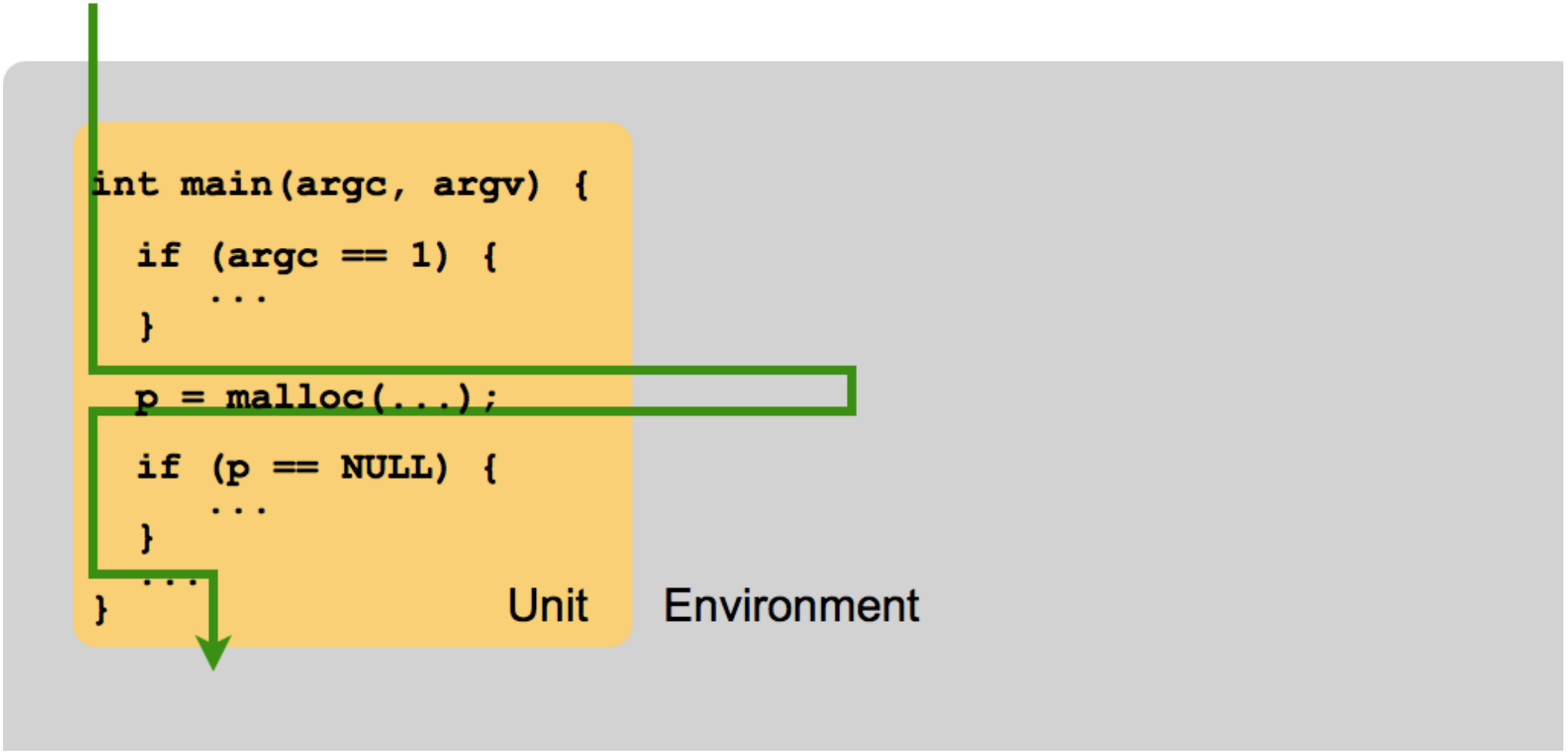
```
int main(argc, argv) {
  if (argc == 1) {
     ...
  }
  p = malloc(...);
  if (p == NULL) {
     ...
  }
  ...
}
```

Unit

Environment

SC-SE

Strictly Consistent *System*-Level Execution



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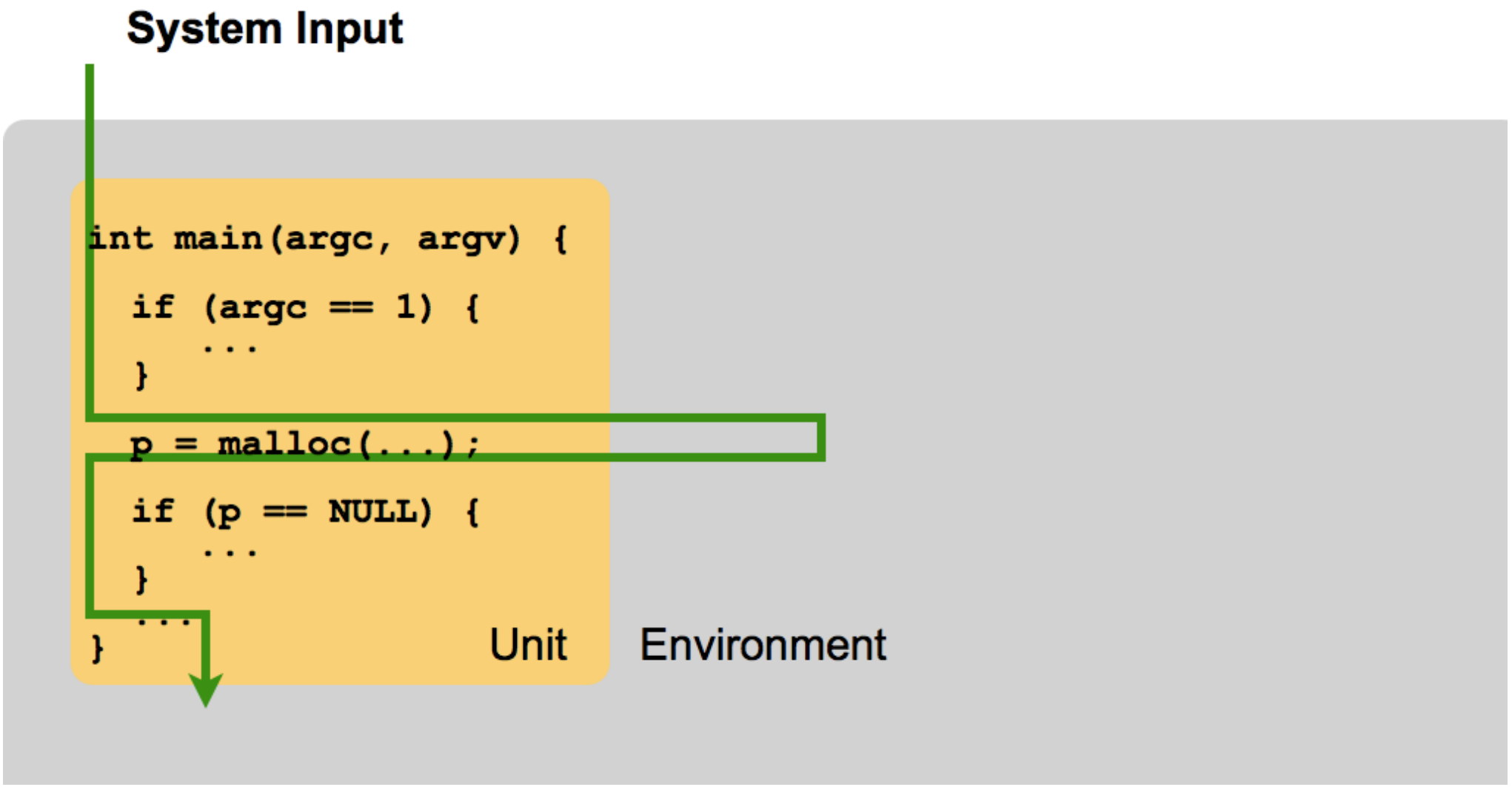

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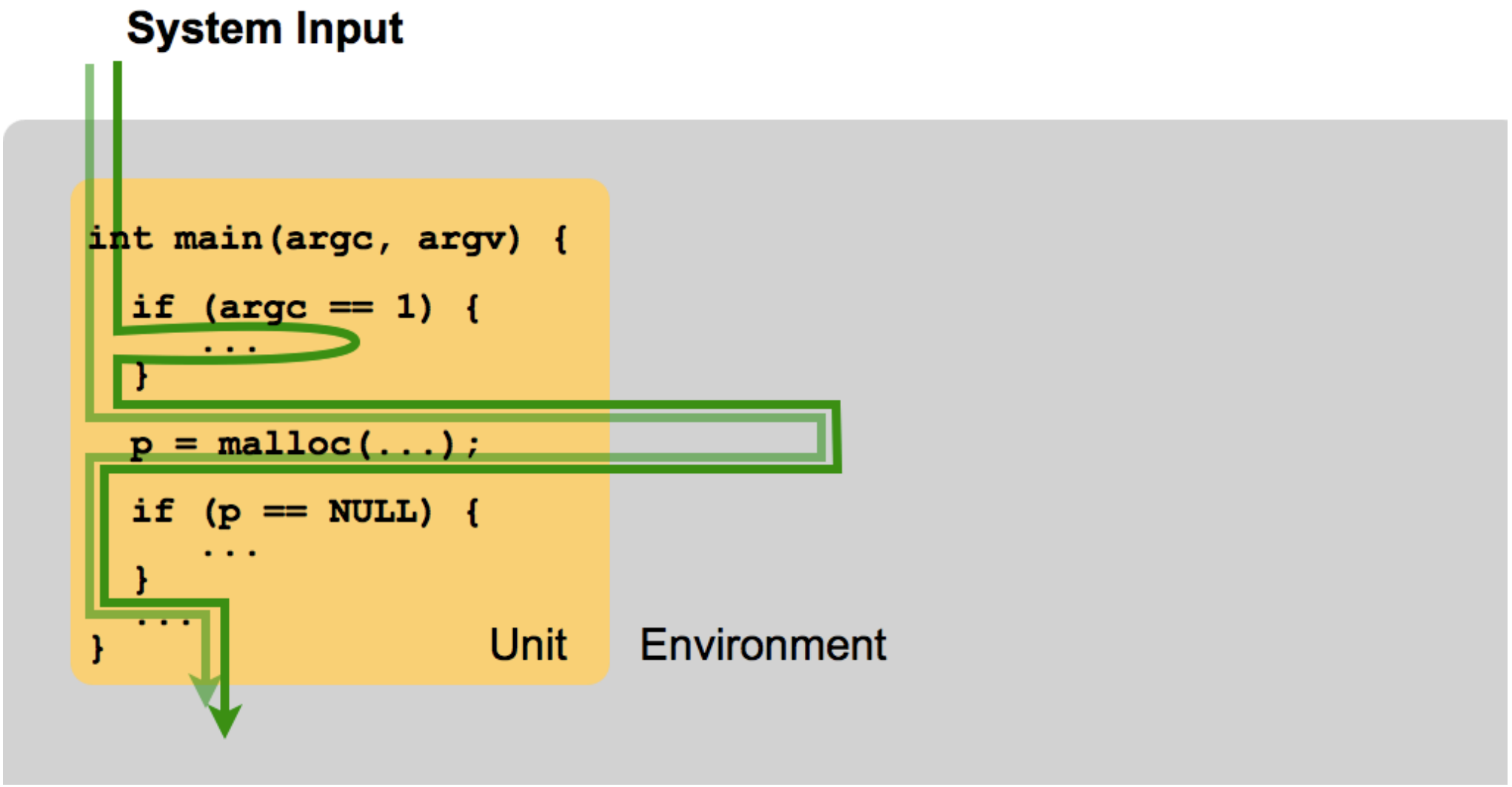

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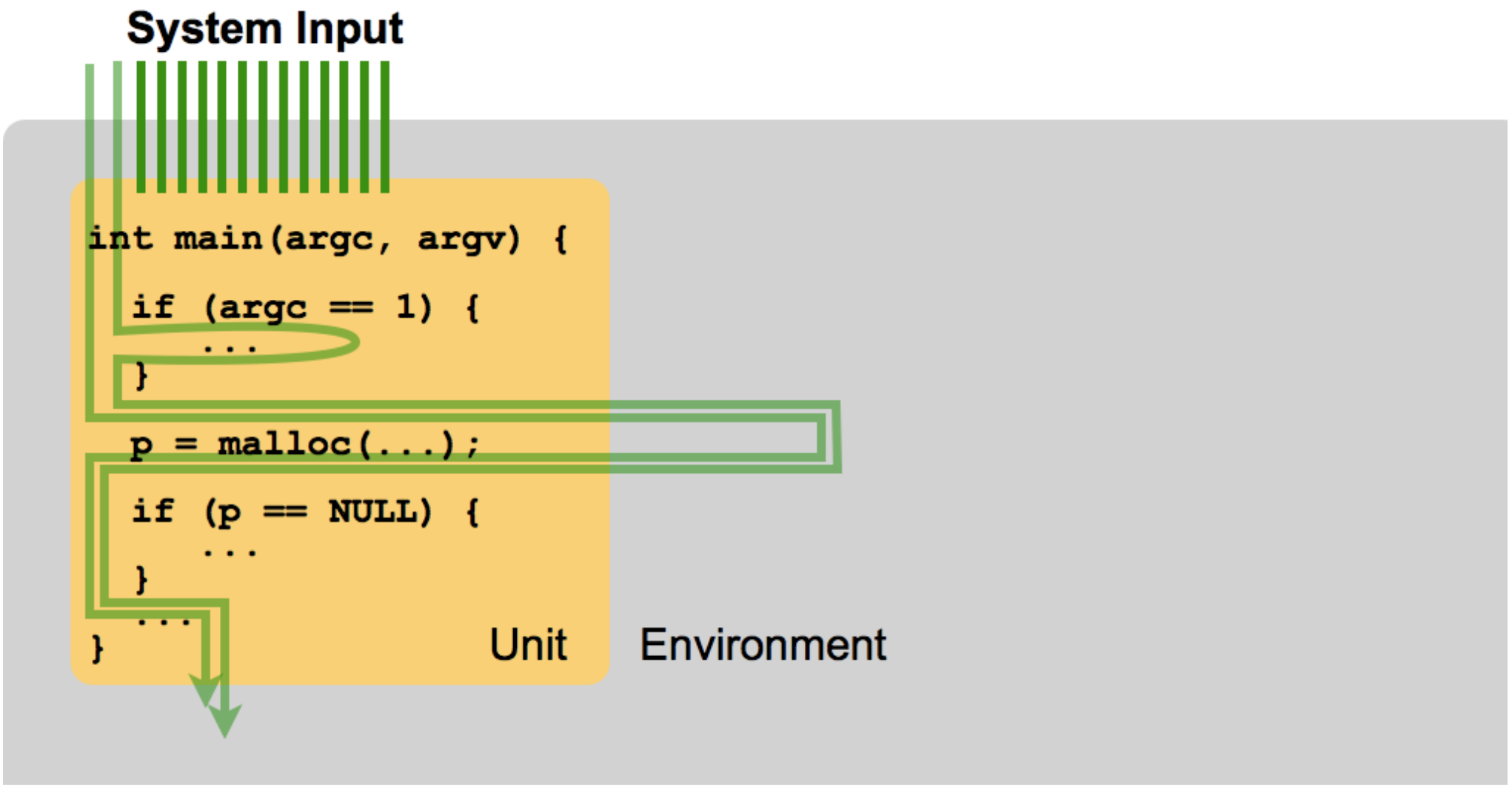

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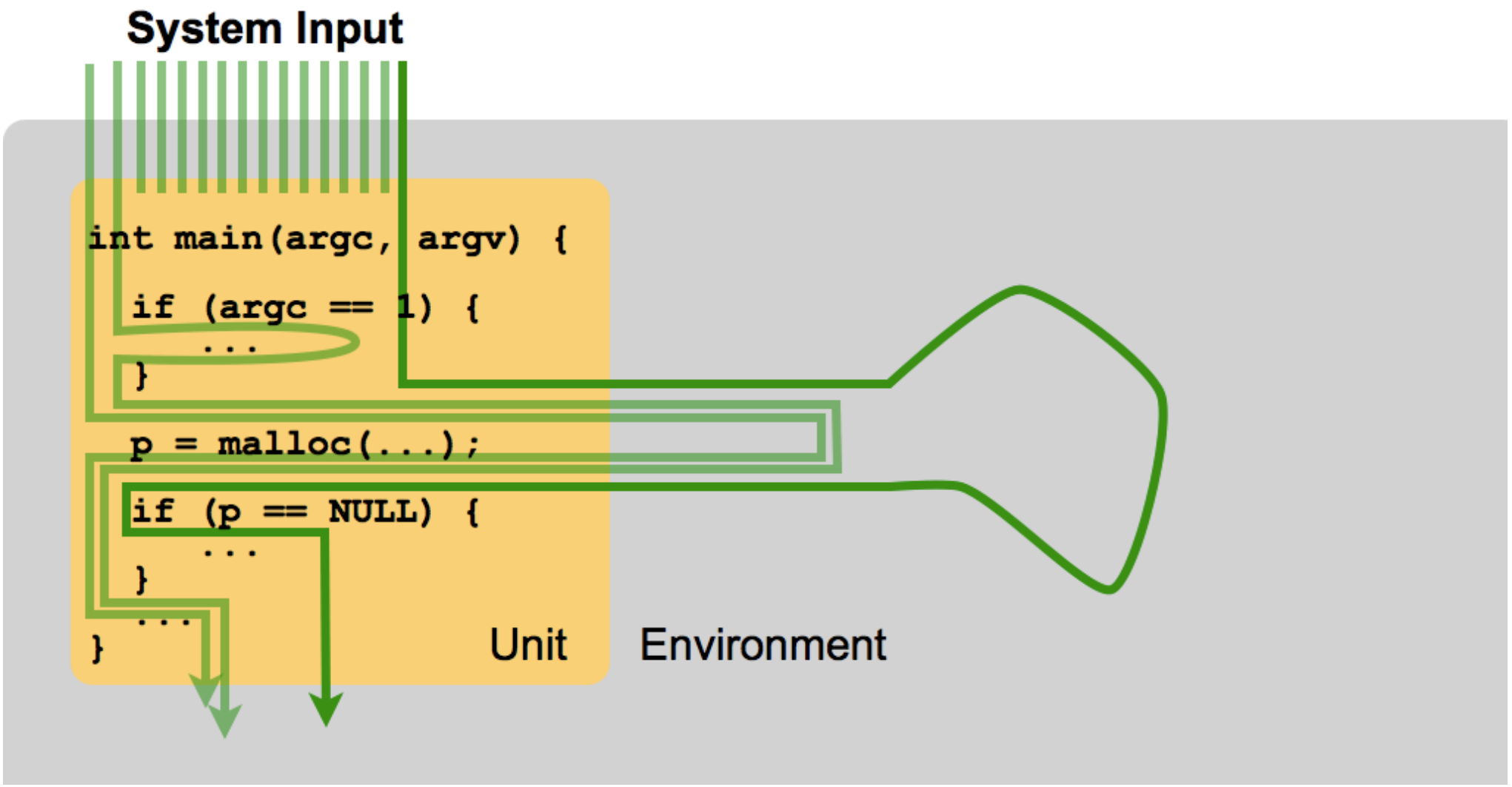

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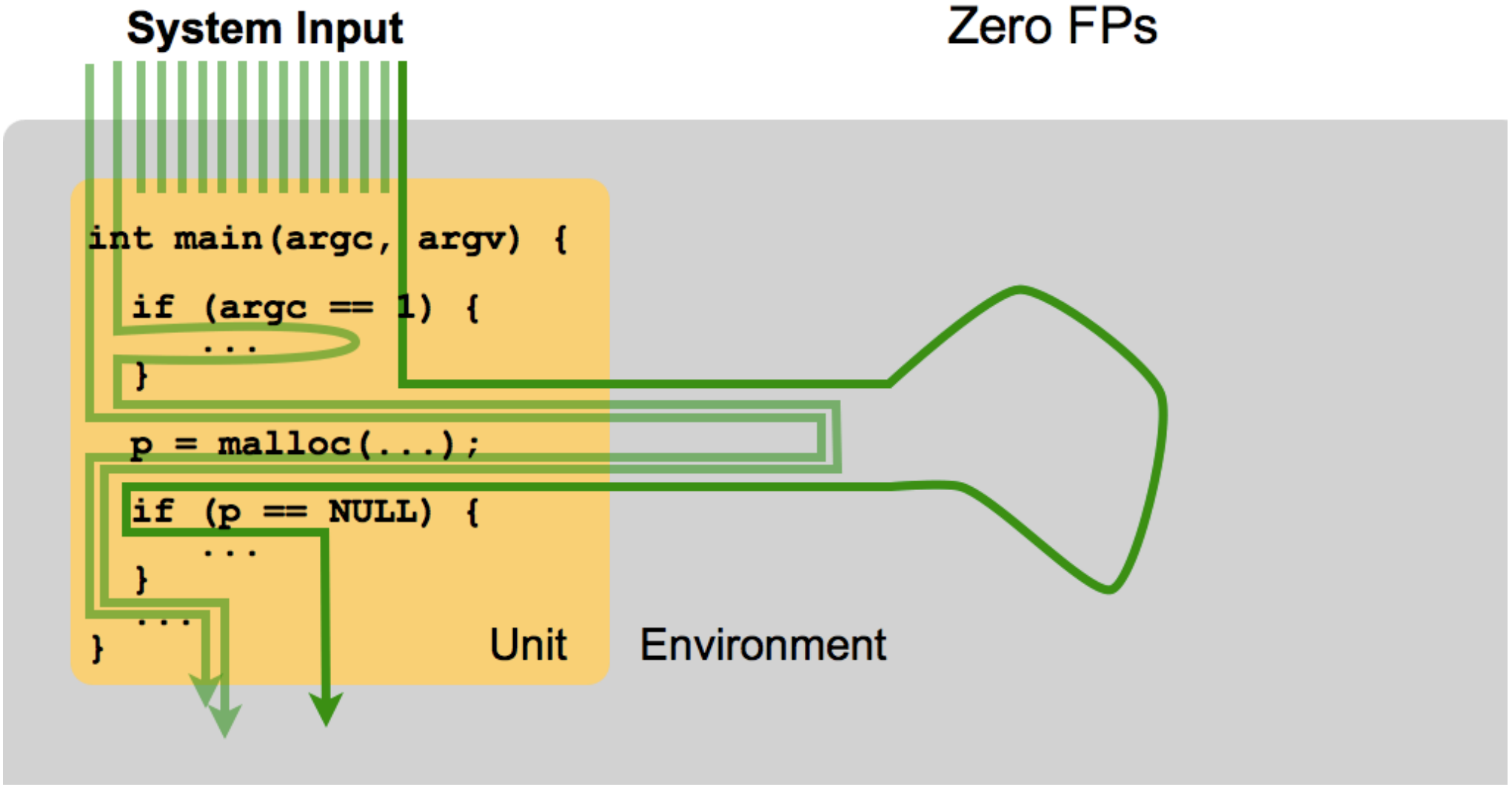
Zero FNs
Zero FPs



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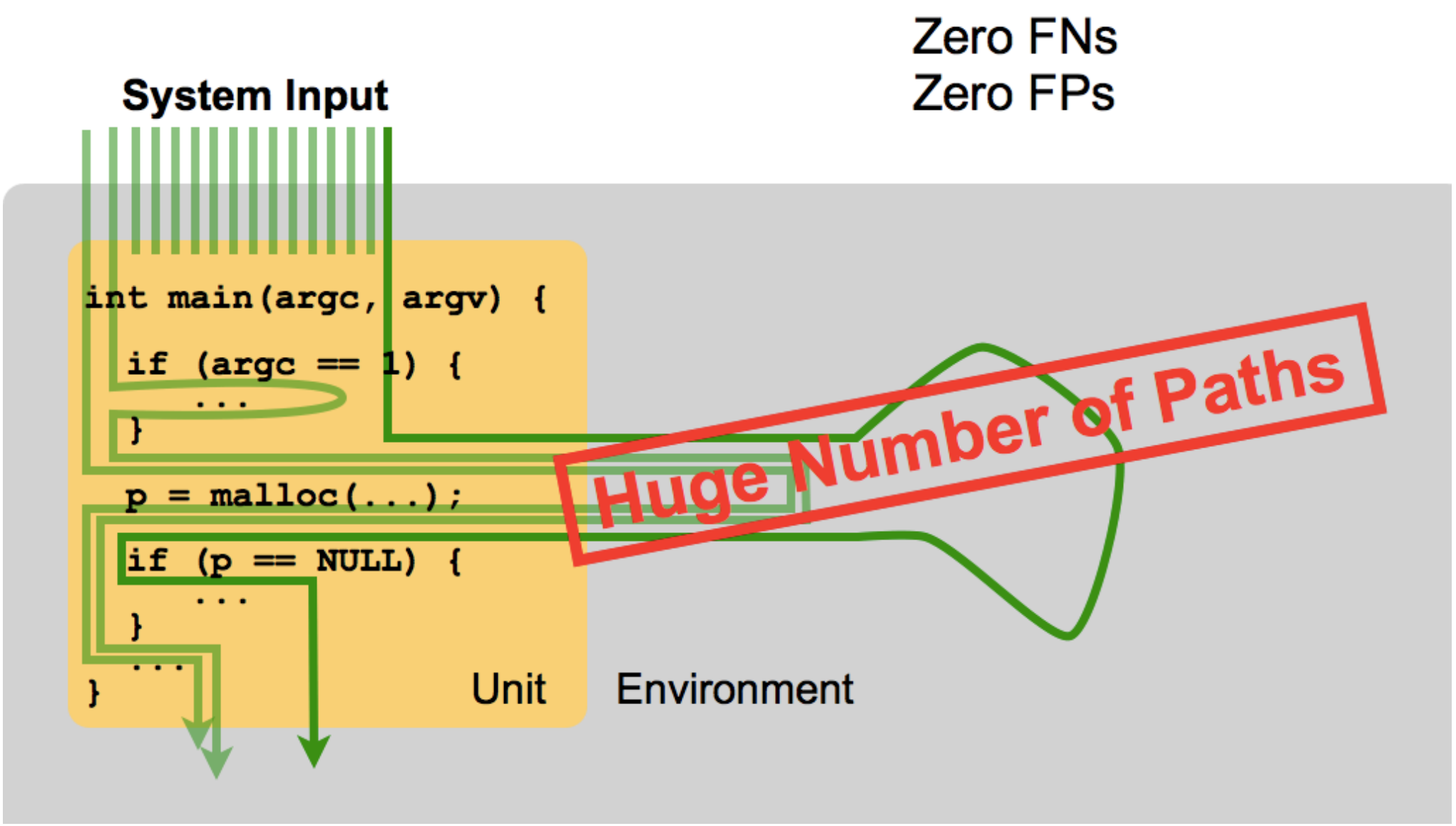
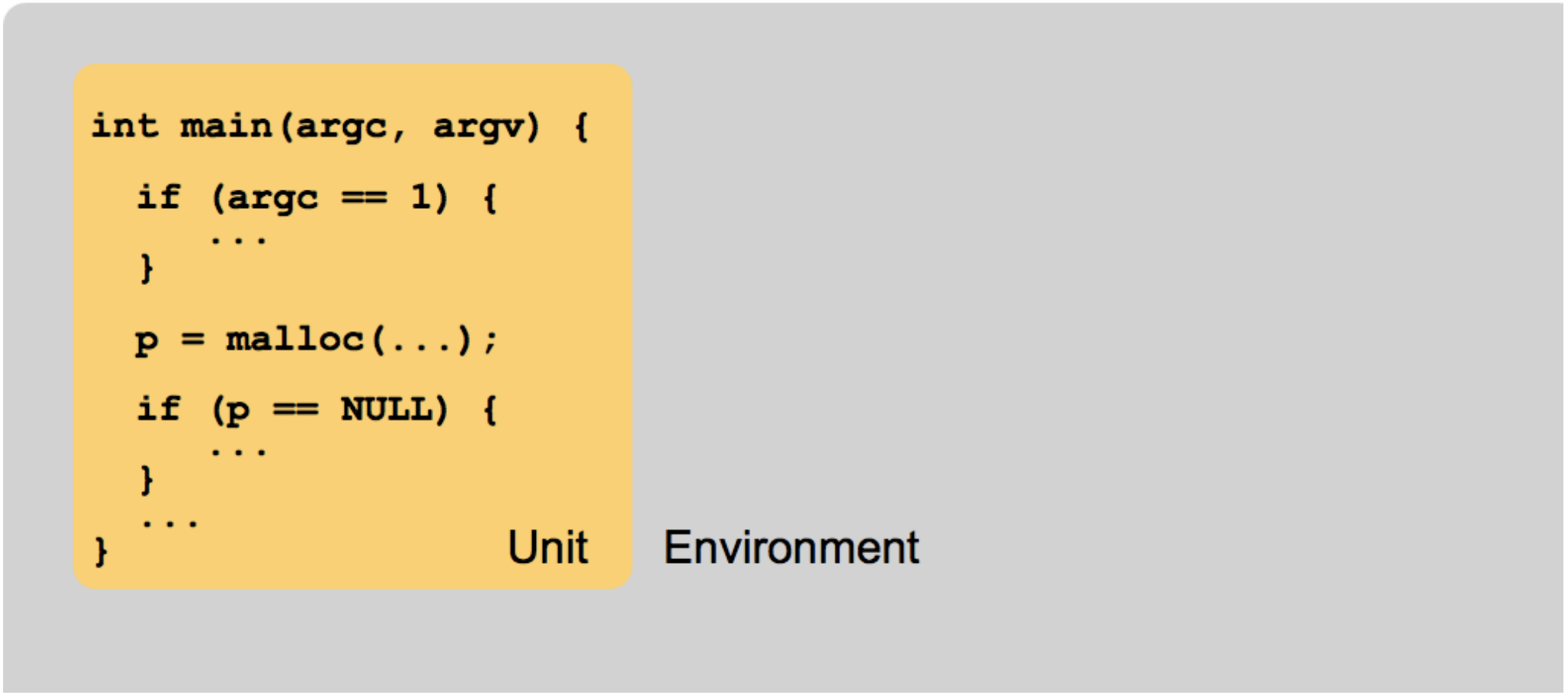


SC-UE

Strictly Consistent *Unit-Level* Execution



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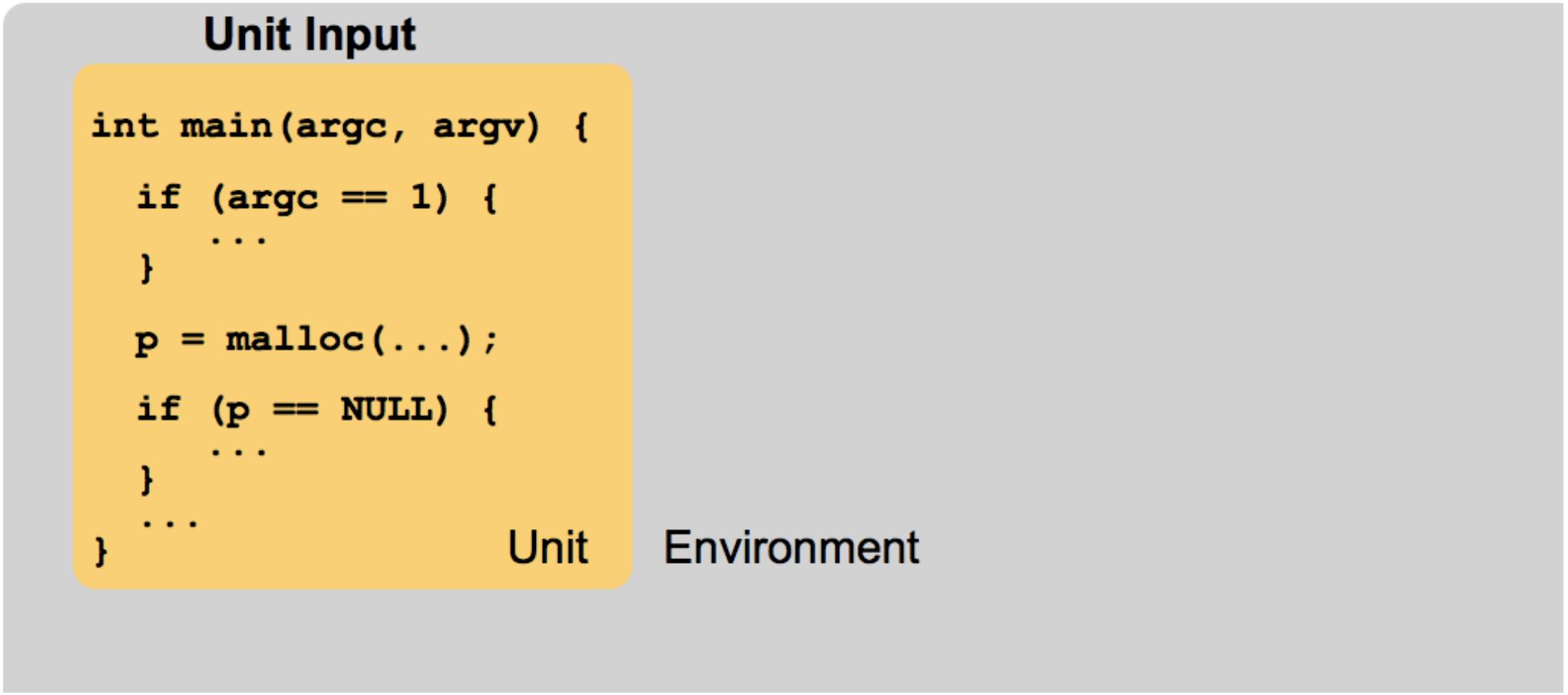

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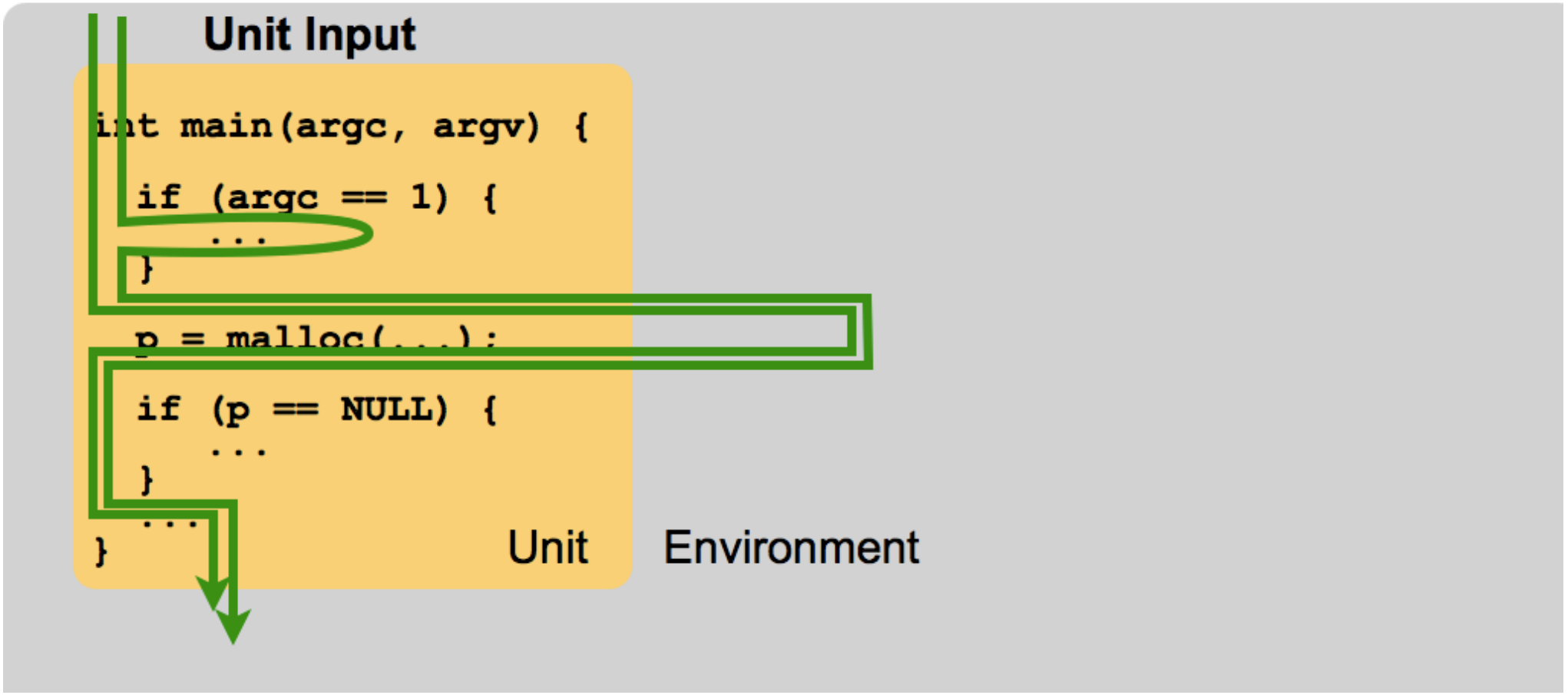

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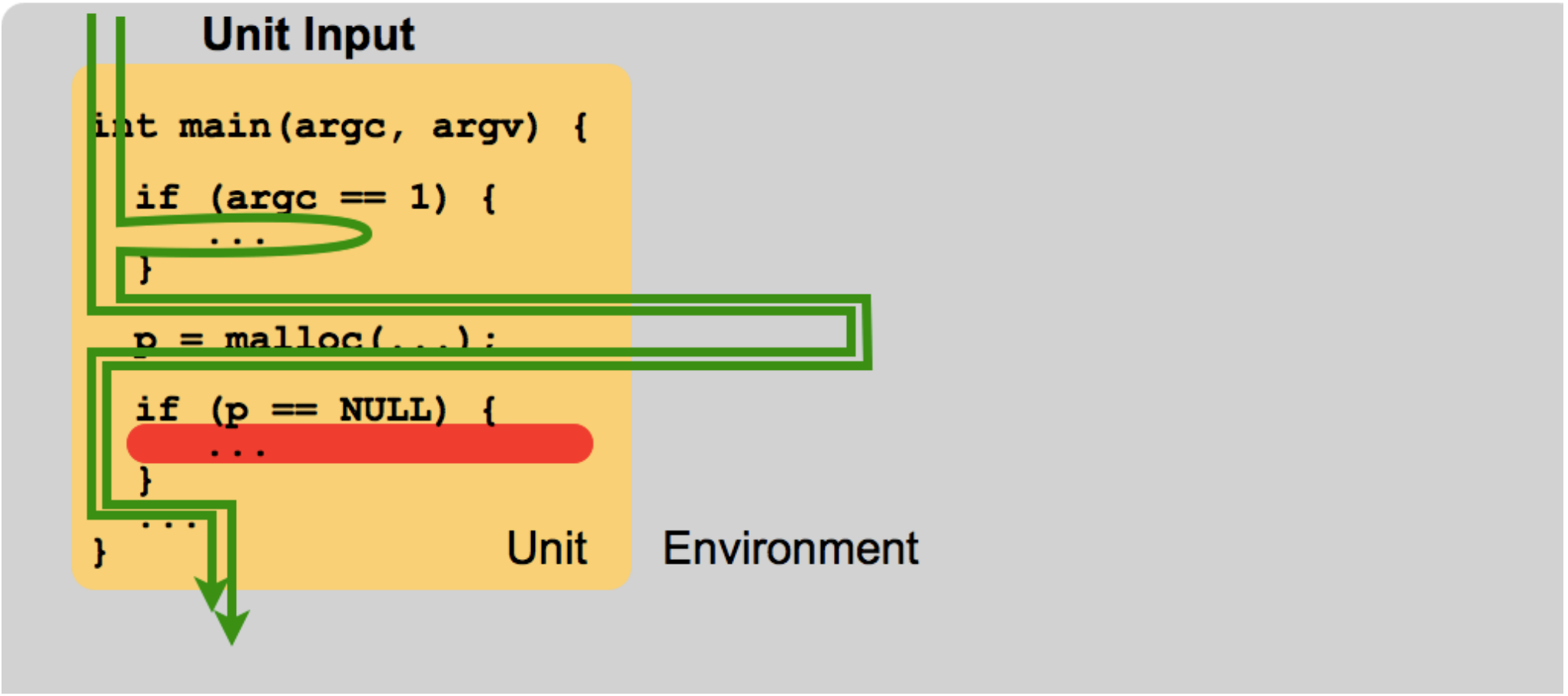
Strictly Consistent *Unit-Level* Execution

Presence of FNs



RC
Relaxed Consistency

Unit Input

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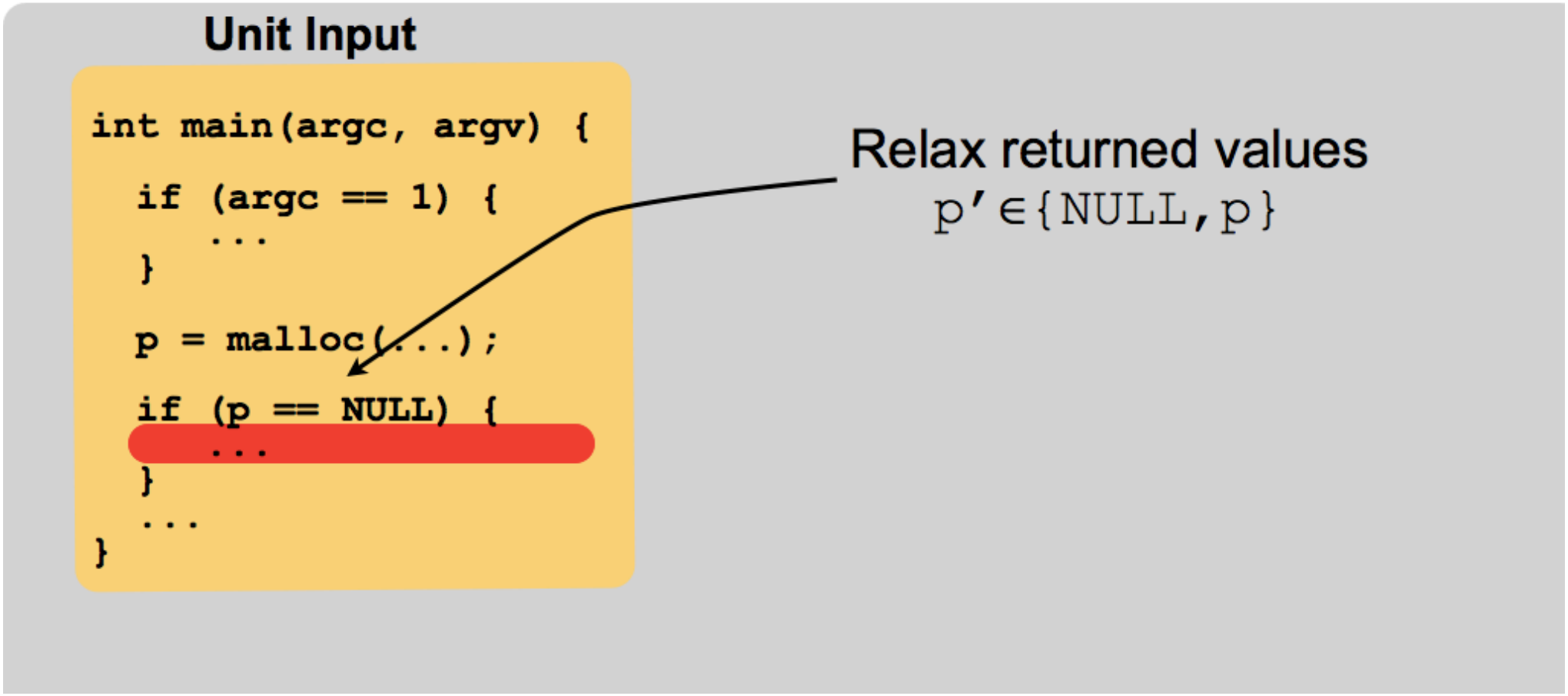

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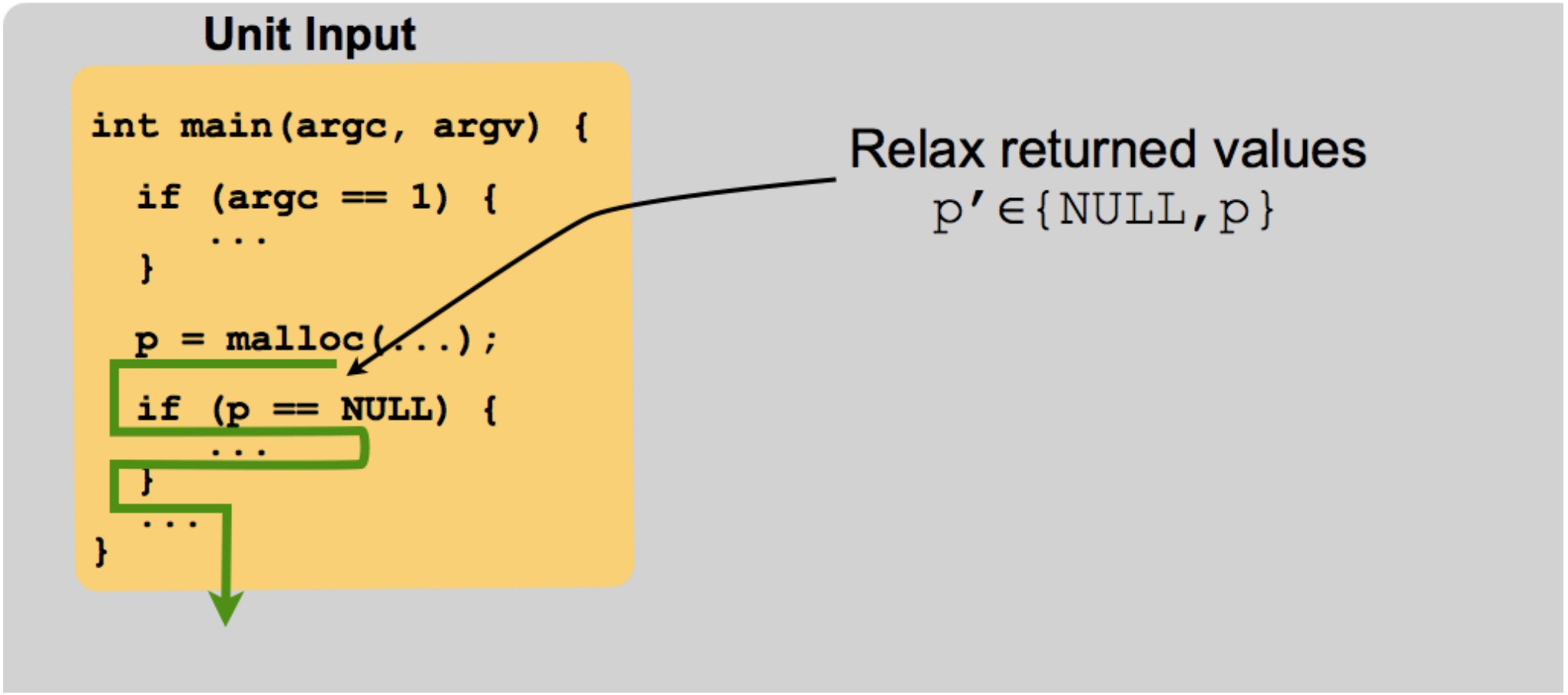

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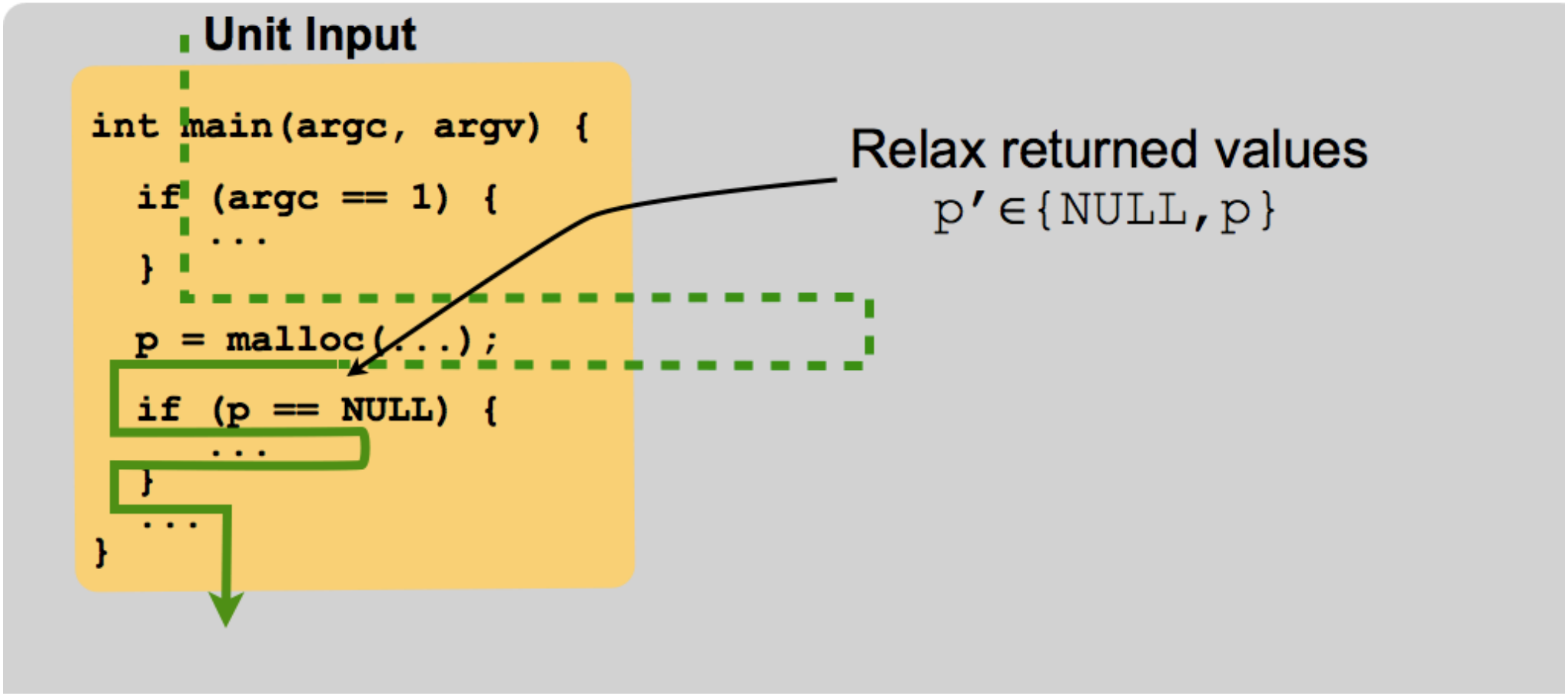

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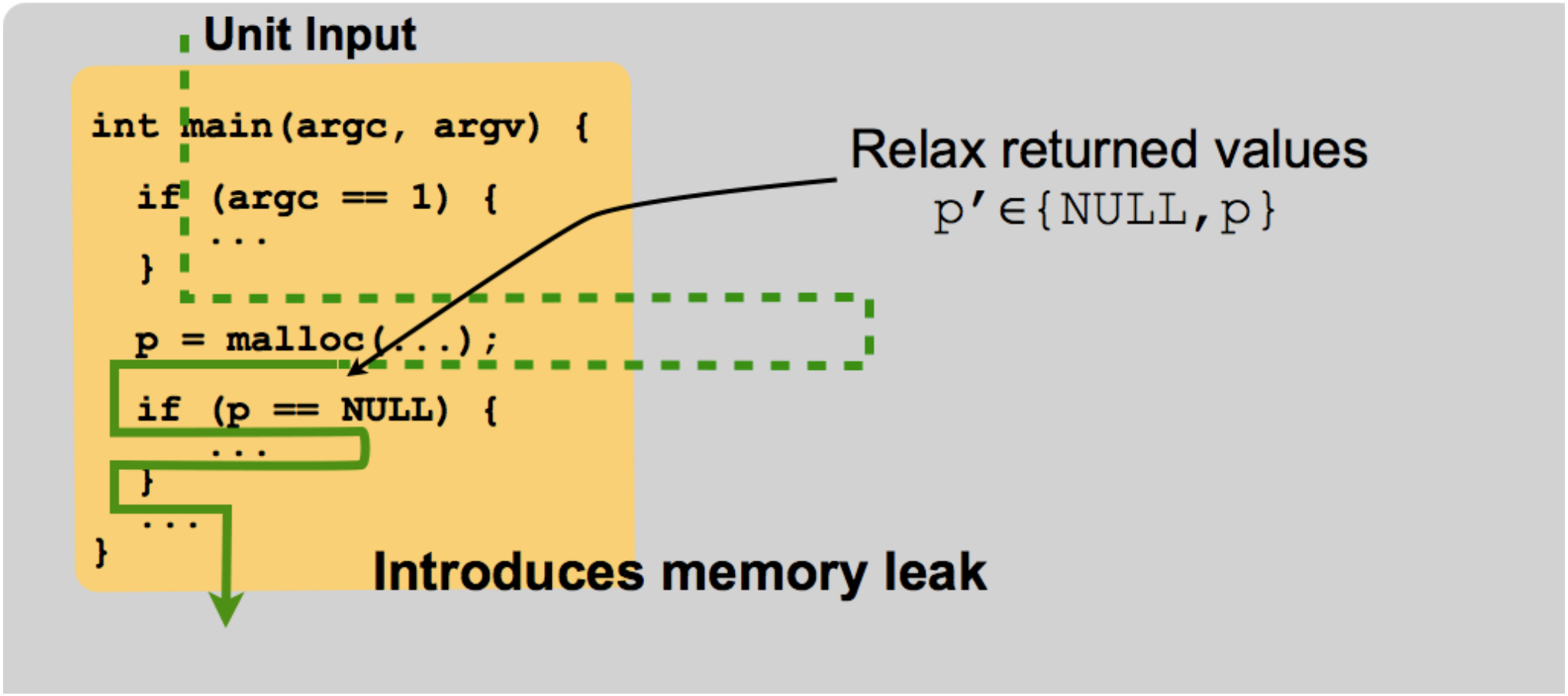
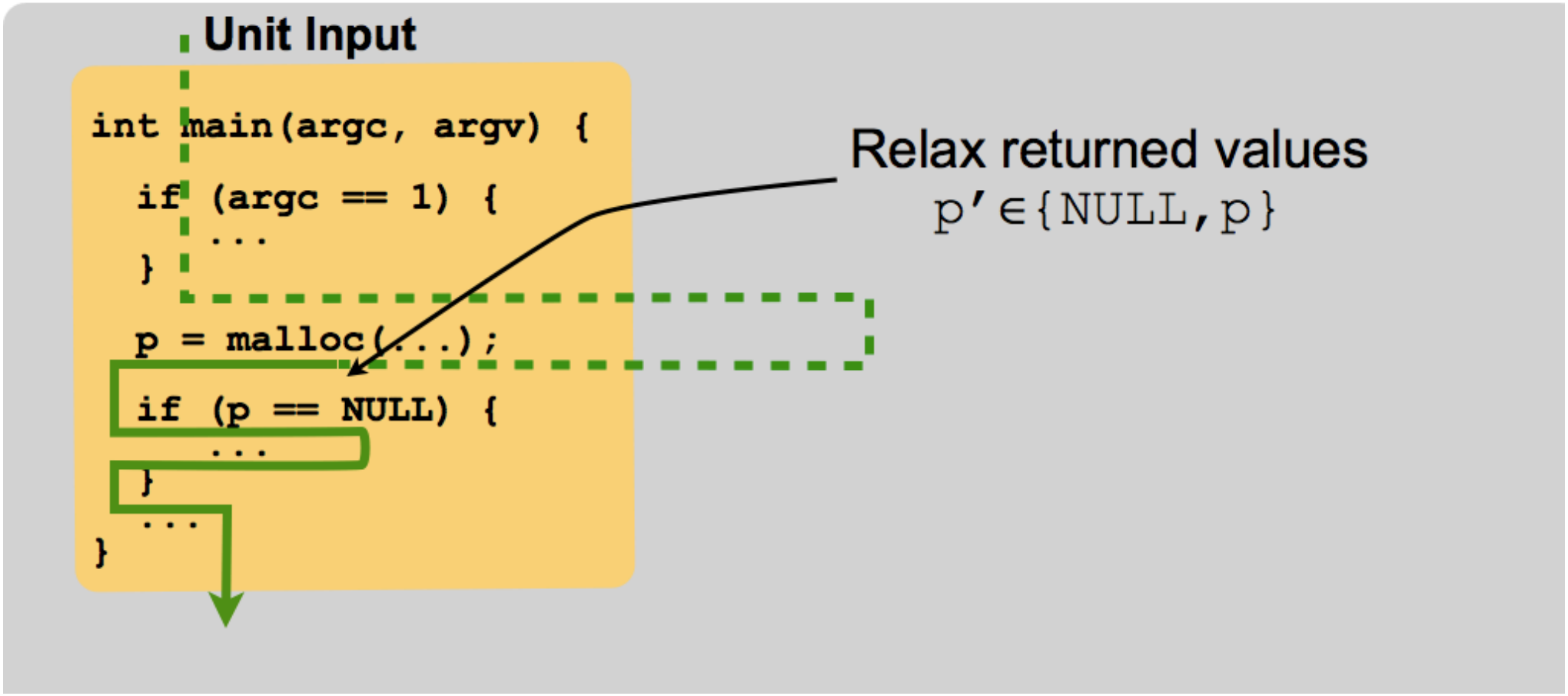


RC
Relaxed Consistency



Execution Consistency Models

Model	FNs w.r.t. unit	FPs w.r.t. unit	# system paths

Execution Consistency Models

Model	FNs w.r.t. unit	FPs w.r.t. unit	# system paths
Concrete			

Execution Consistency Models

Model	FNs w.r.t. unit	FPs w.r.t. unit	# system paths
Concrete			
SC-SE			

Execution Consistency Models

Model	FNs w.r.t. unit	FPs w.r.t. unit	# system paths
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SC-UE			

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CFG			

Execution Consistency Models

Model	FNs w.r.t. unit	FPs w.r.t. unit	# system paths
Concrete			
SC-SE			
SC-UE			
RC			
CFG			
Local			

Execution Consistency Models

Model	FNs w.r.t. unit	FPs w.r.t. unit	# system paths	Uses
Concrete				Valgrind
SC-SE				KLEE
SC-UE				DART
RC				RevNIC
CFG				Disassemblers
Local				DDT

Execution Consistency Models

Model	FNs w.r.t. unit	FPs w.r.t. unit	# system paths	Uses
Concrete				Valgrind
SC-SE				KLEE
SC-UE				DART
RC				RevNIC
CFG				Disassemblers
Local				DDT

Design your own models

Outline

- Theory
  Execution consistency models
- System
  S²E: Platform for in-vivo multi-path analysis
- Results
  Using S²E in practice

http://s2e.epfl.ch

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Symbolic Execution

Symbolic Execution

```
int func(int a, int b)
{

  if (a > 0) {
     ...
  }

  if (b < 0) {
  ...
  }

}
```

Symbolic Execution

```
a=1 b=2  a=3 b=5  a=5 b=2  a=10 b=22
```

```
int func(int a, int b)
{

  if (a > 0) {
      ...
  }

  if (b < 0) {
  ...
  }

}
```

Symbolic Execution

a=λ b=δ

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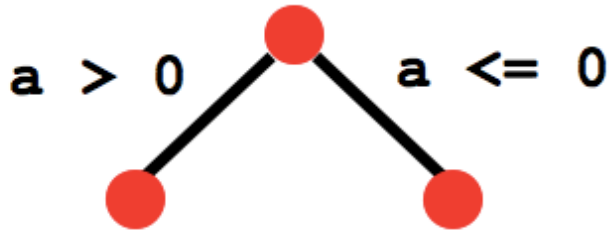

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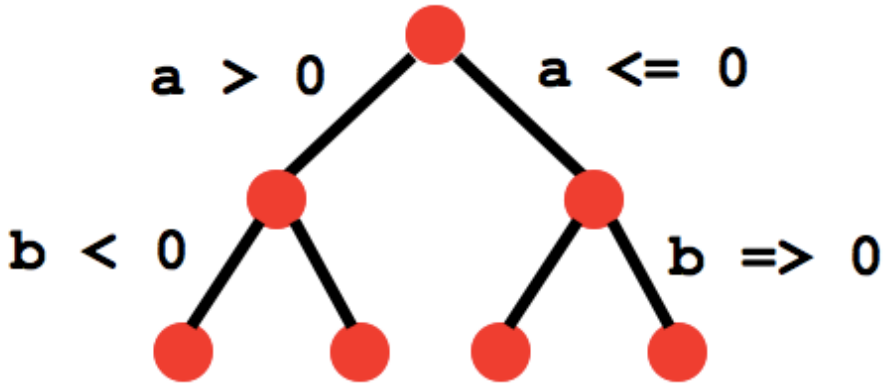


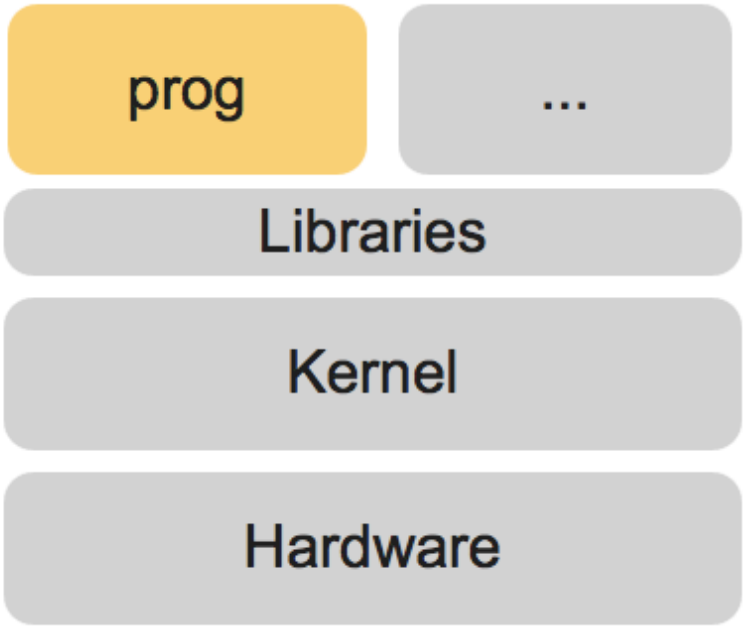
Concrete ➡ Symbolic

```
int main(argc, argv) {

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

  p = malloc(...);

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



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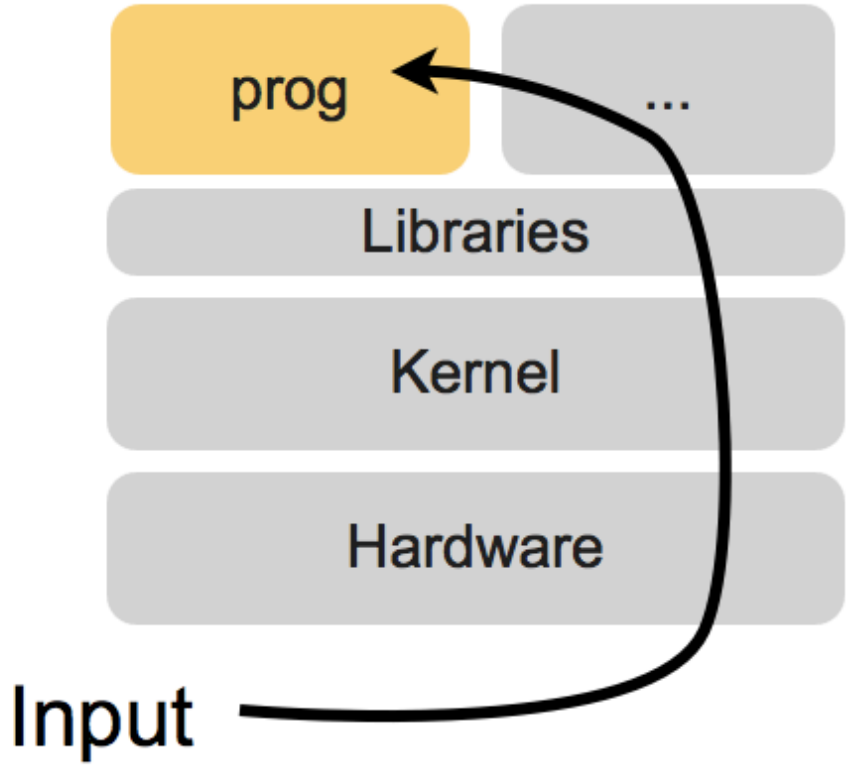

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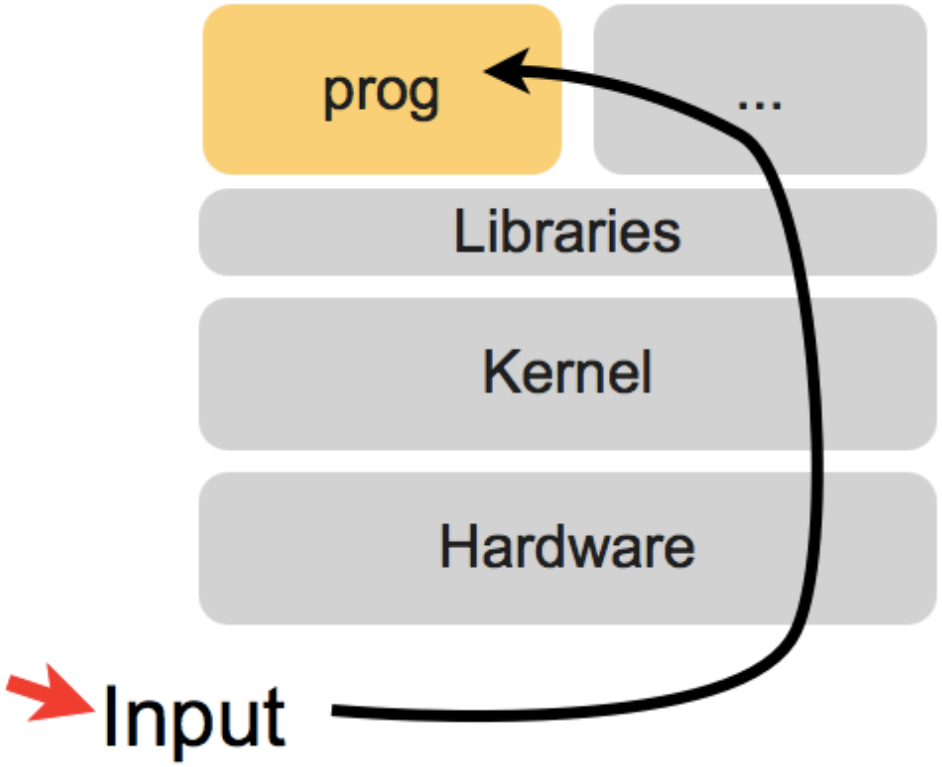

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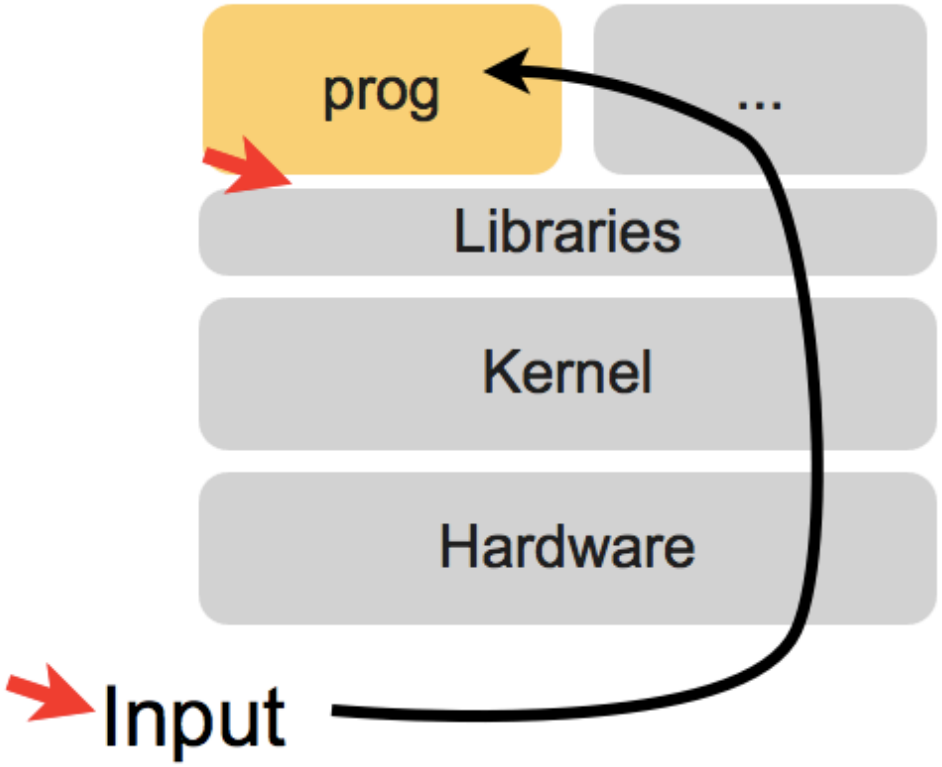

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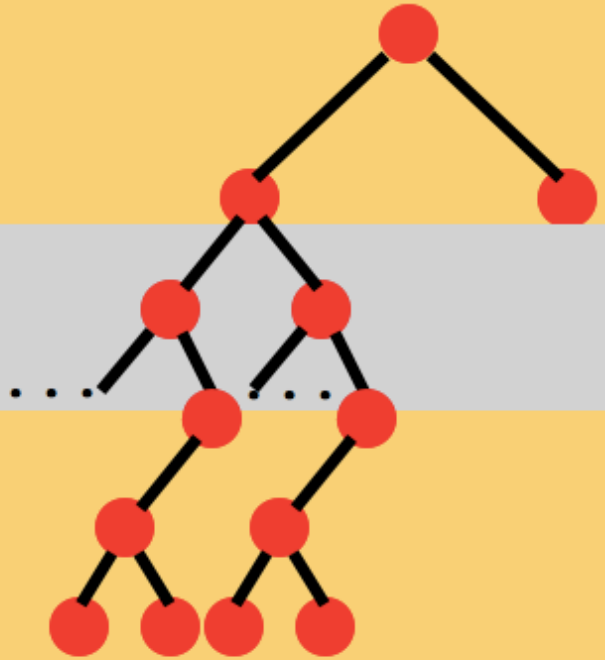
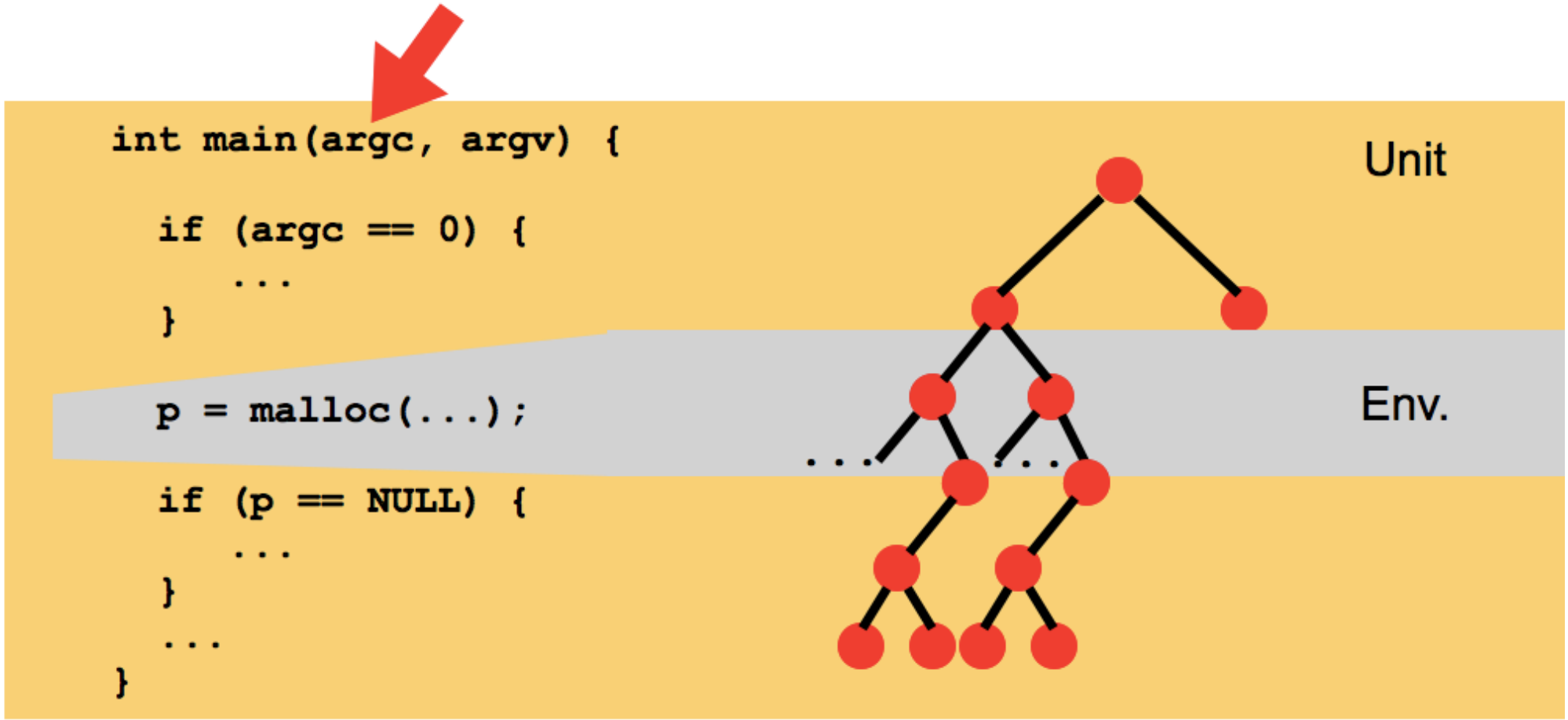
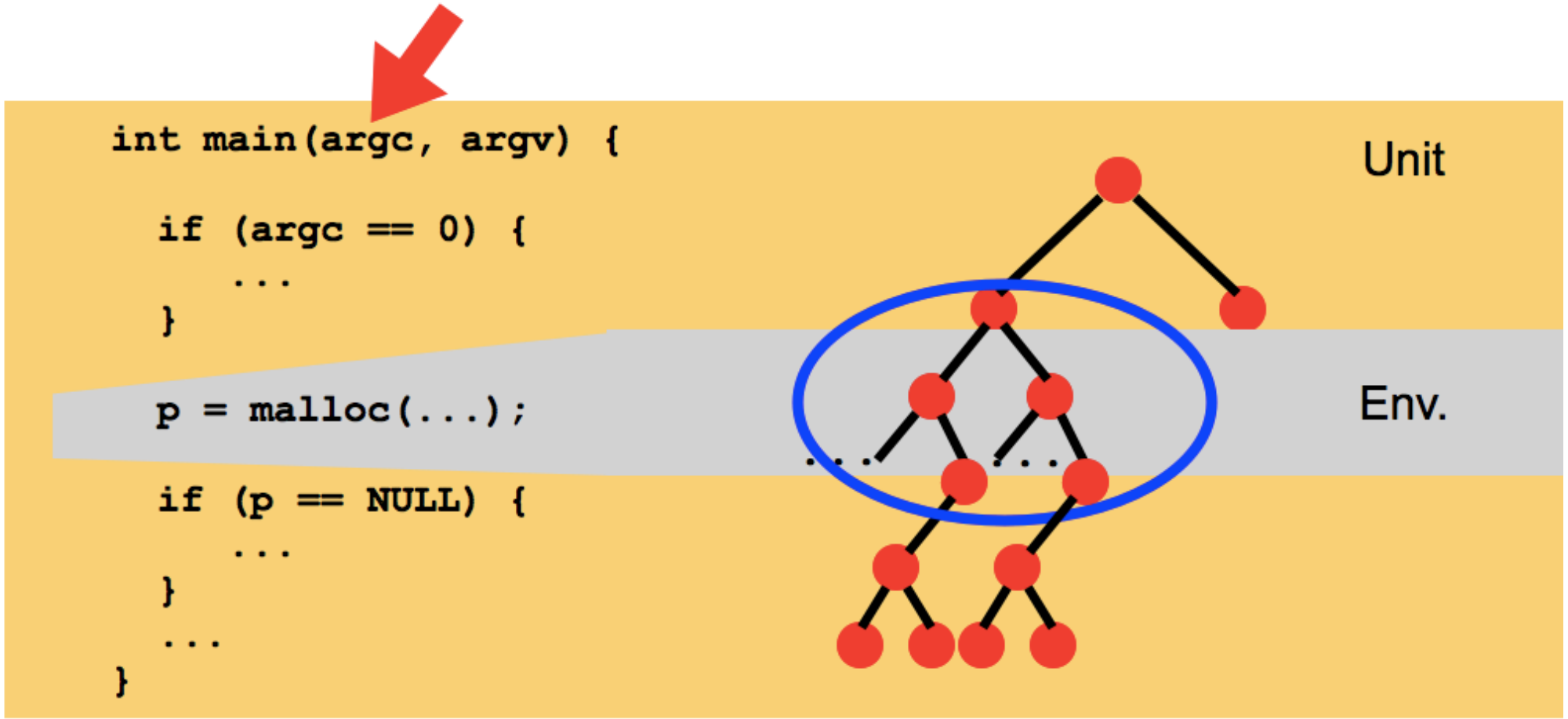


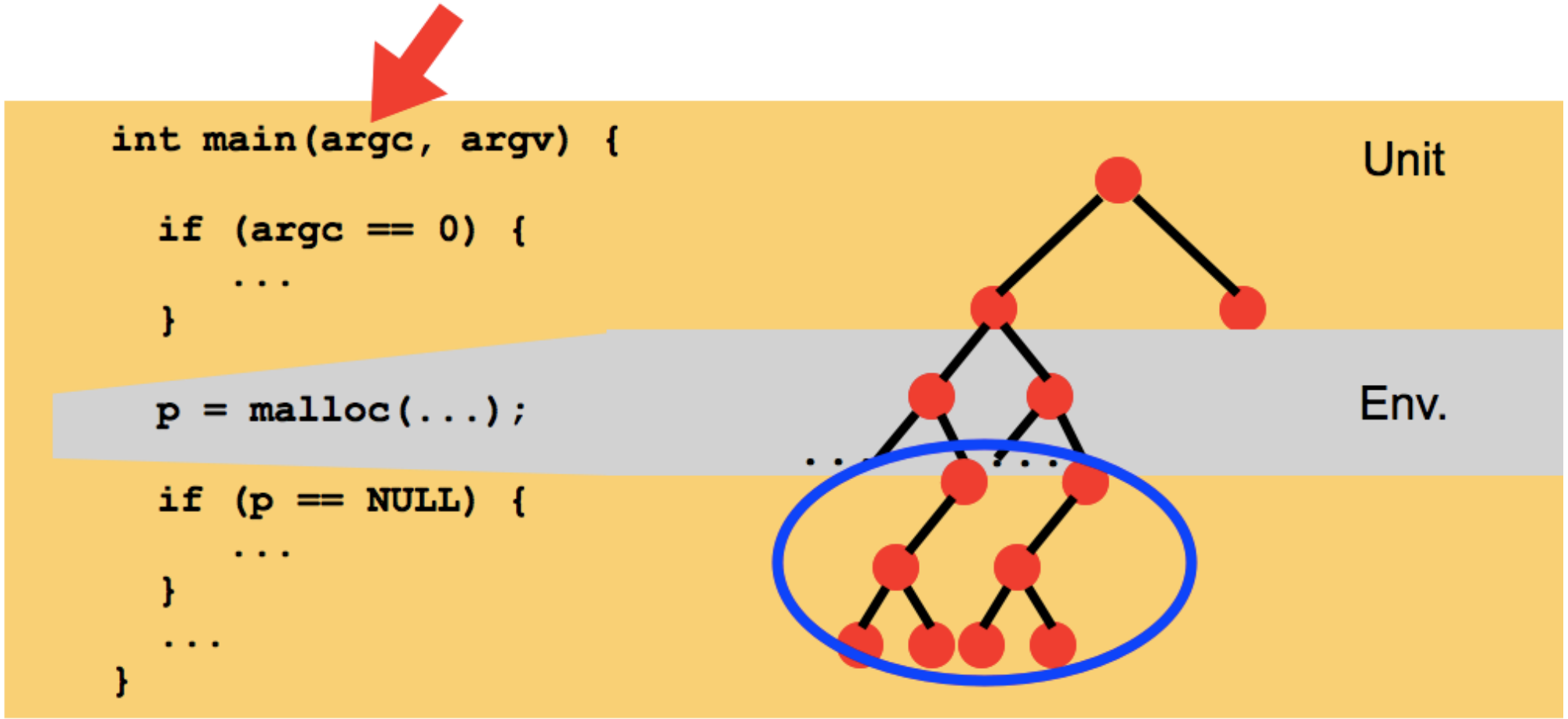
Concrete ➡ Symbolic



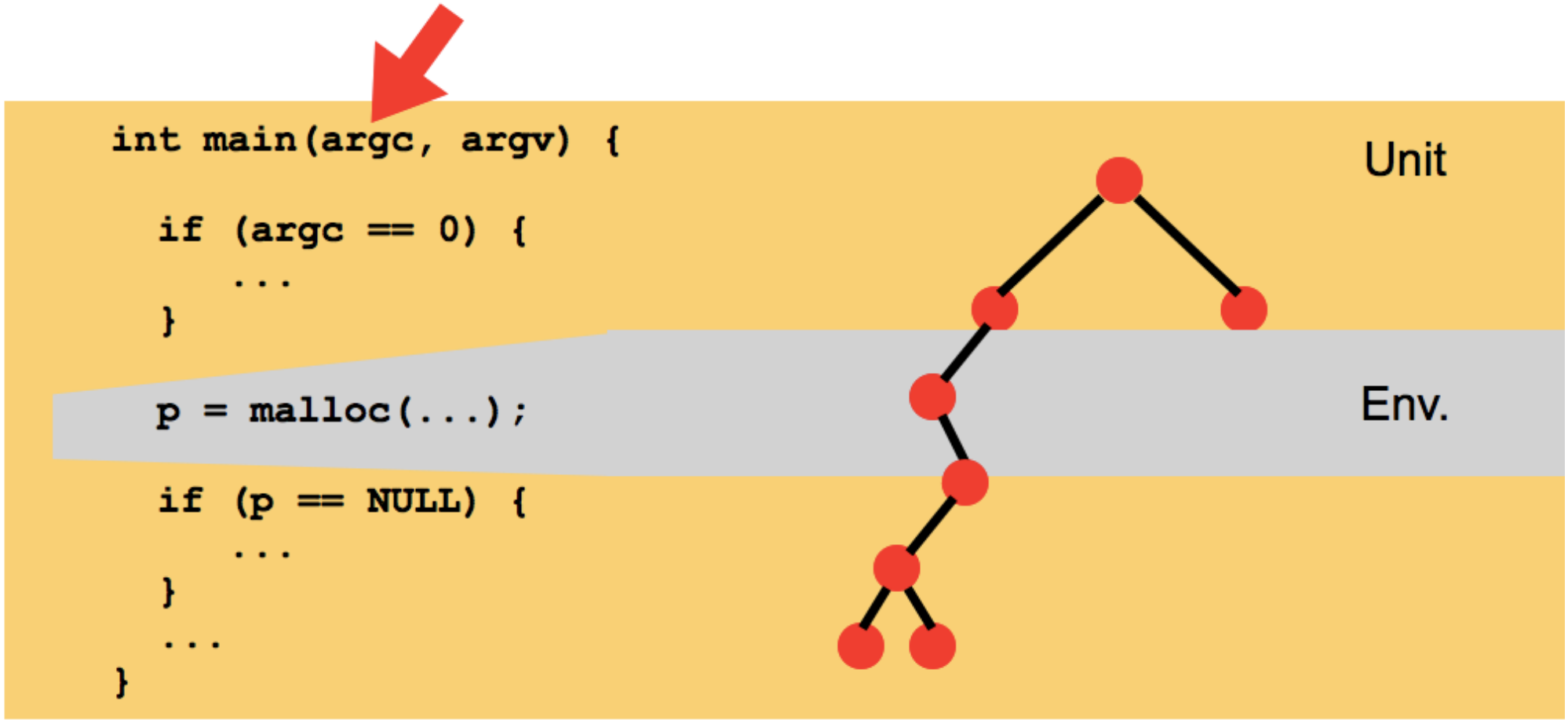
Concrete ➡ Symbolic



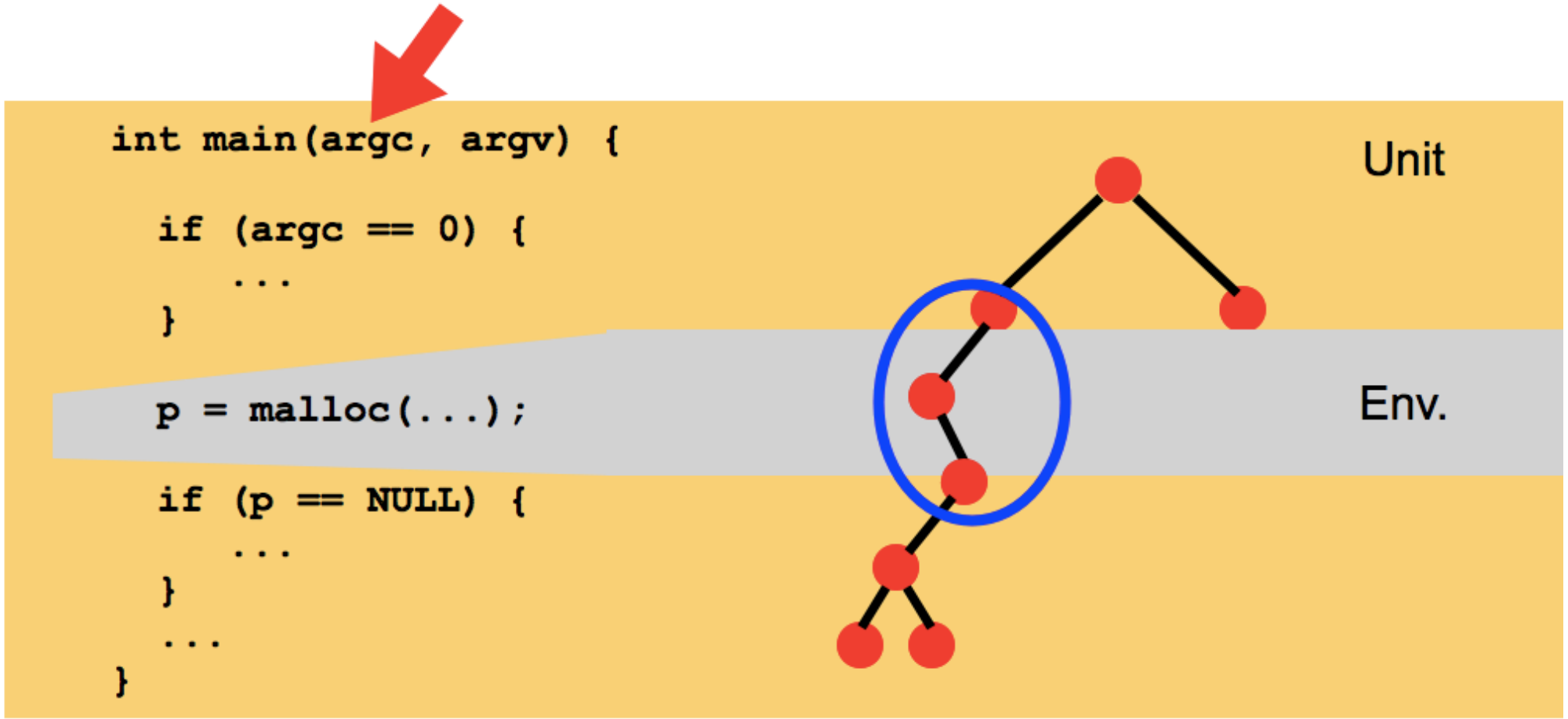
Concrete ➡ Symbolic



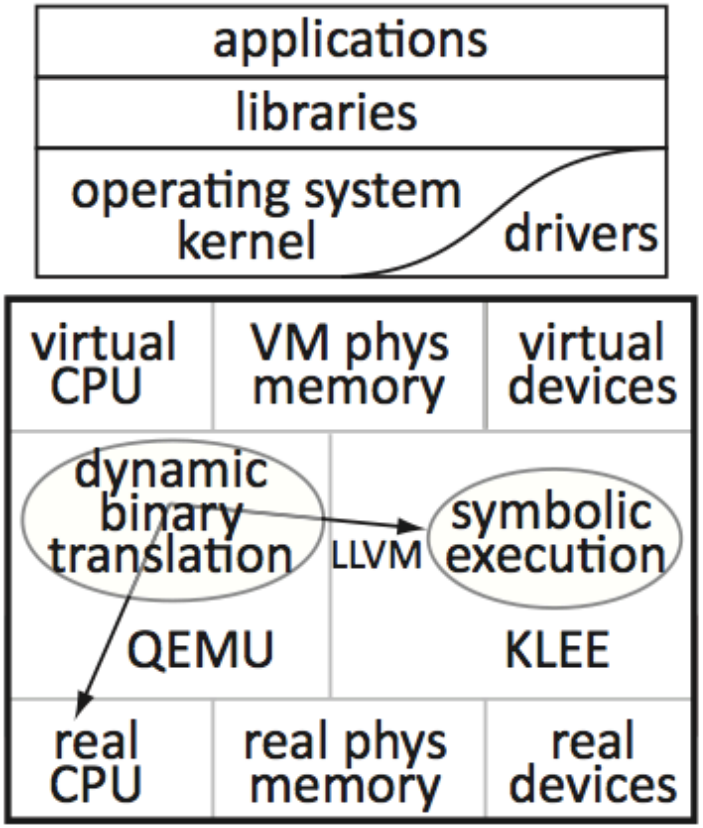
Symbolic ➡ Concrete



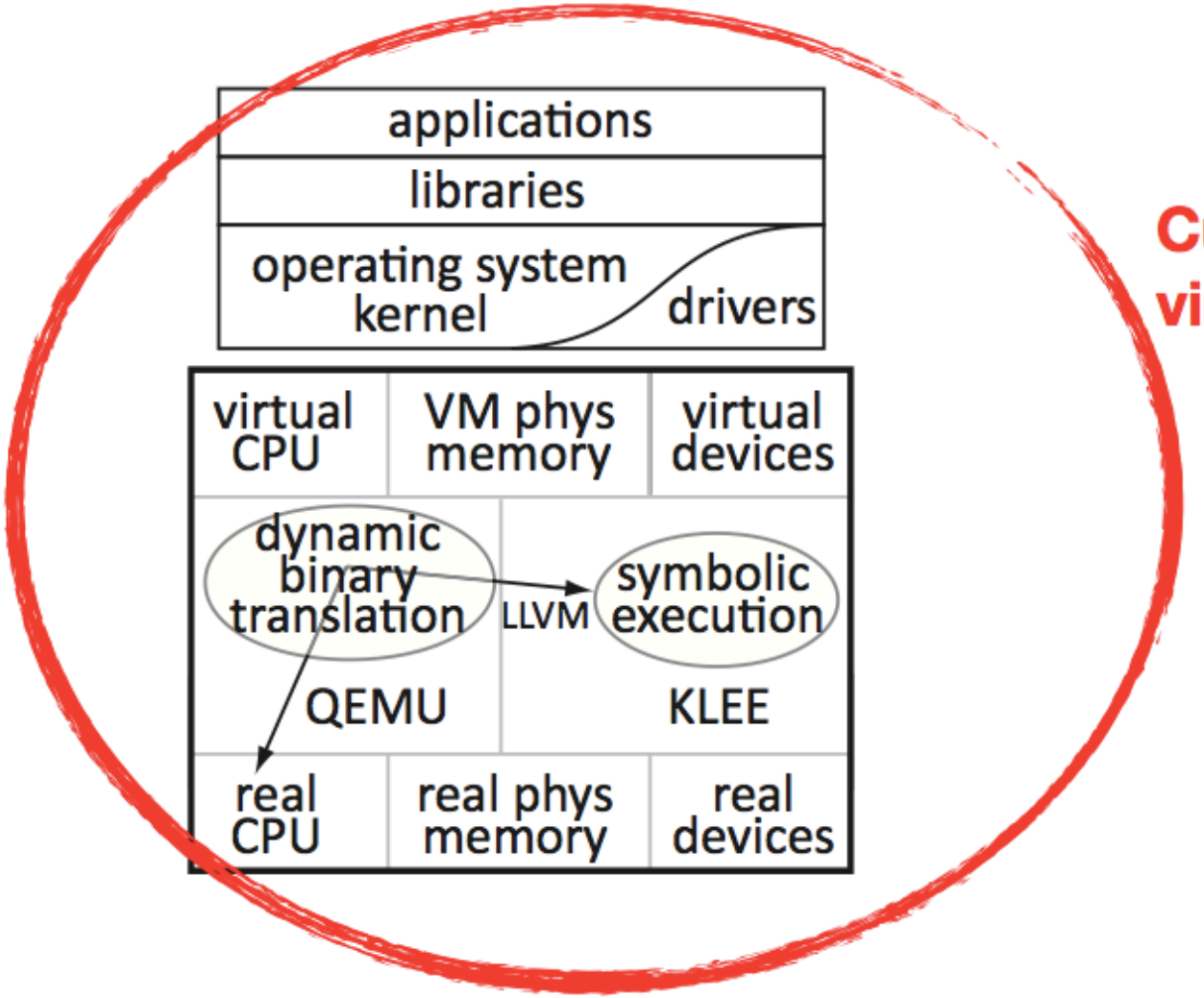
Symbolic ➡ Concrete



S2E Is A Virtual Machine

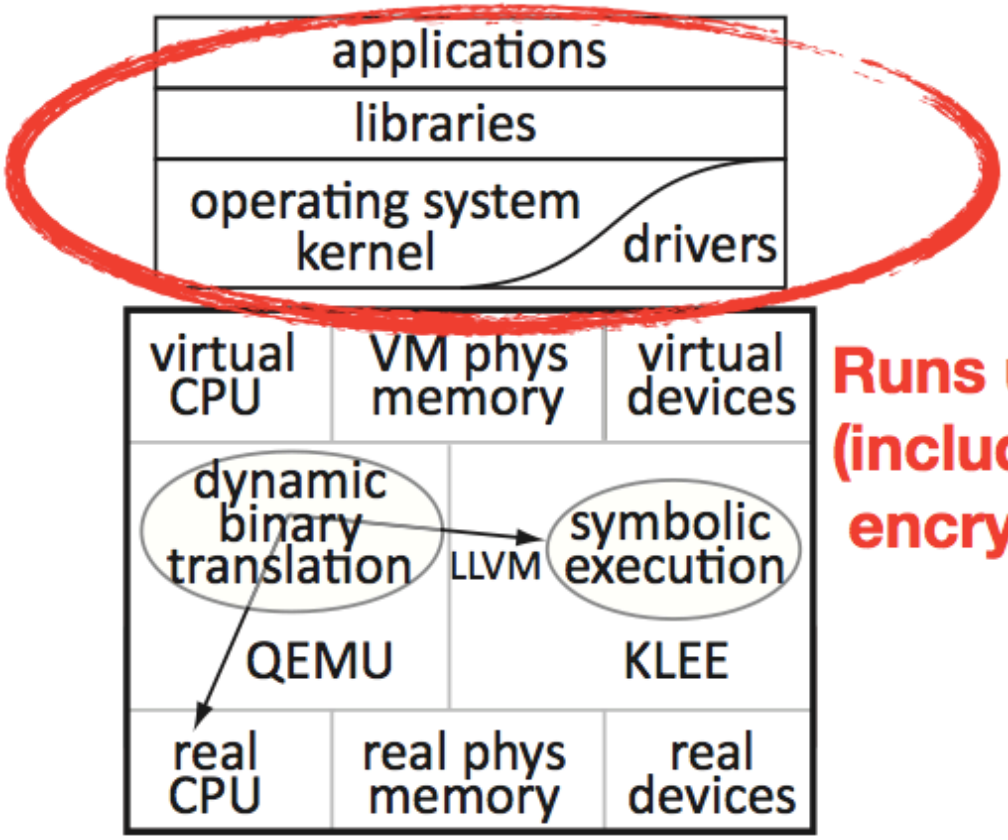


S2E Is A Virtual Machine



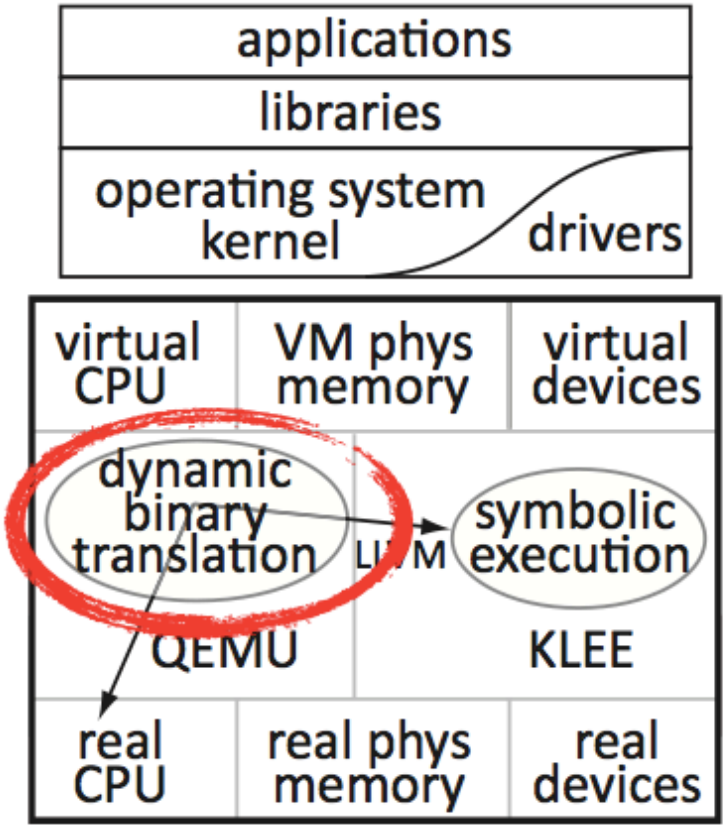
Customized virtual machine

S2E Is A Virtual Machine



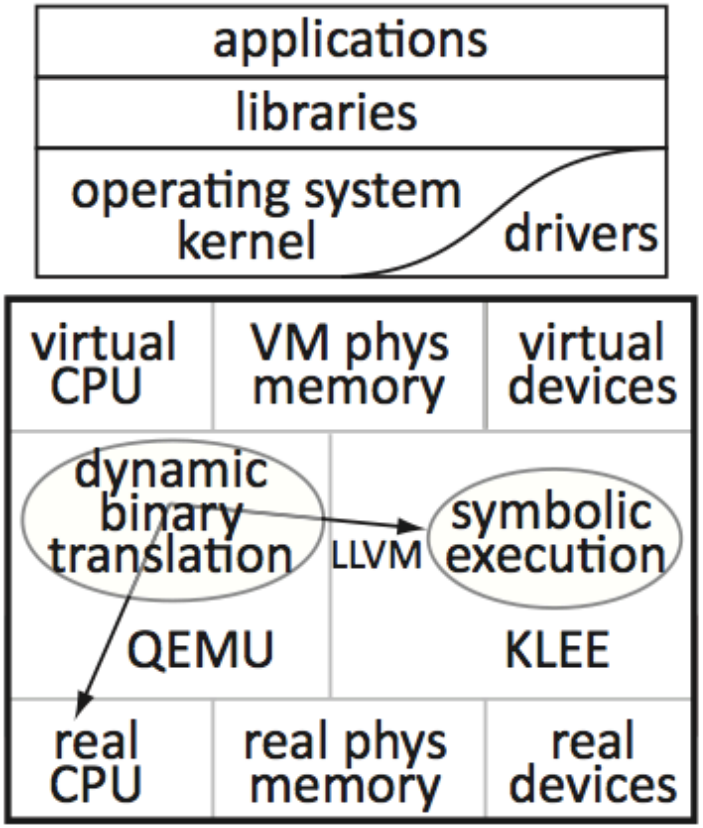
Runs unmodified x86 binaries (including proprietary/obfuscated/ encrypted binaries)

S2E Is A Virtual Machine



Selection done at runtime
Most code runs "natively"

S2E Is A Virtual Machine



Shared concrete/symbolic state representation

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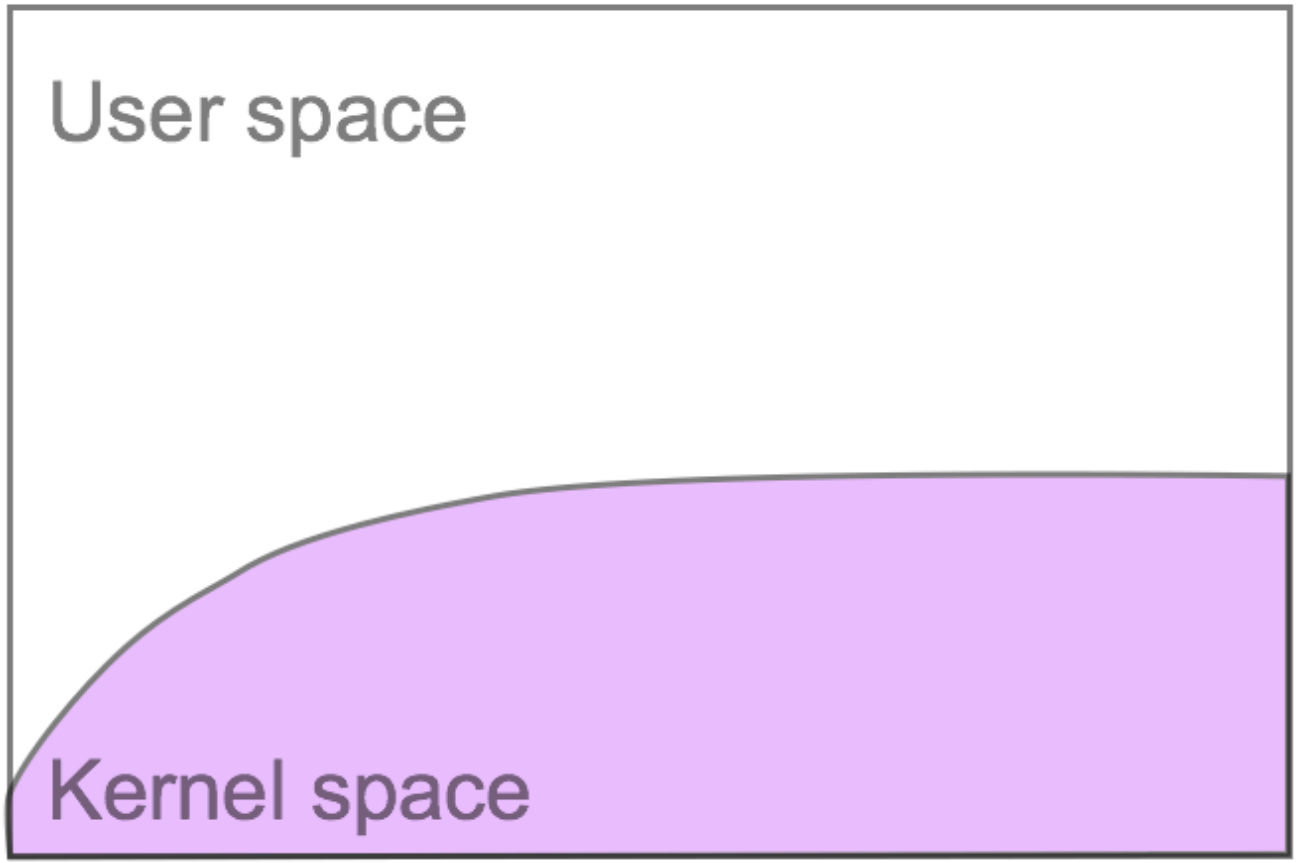
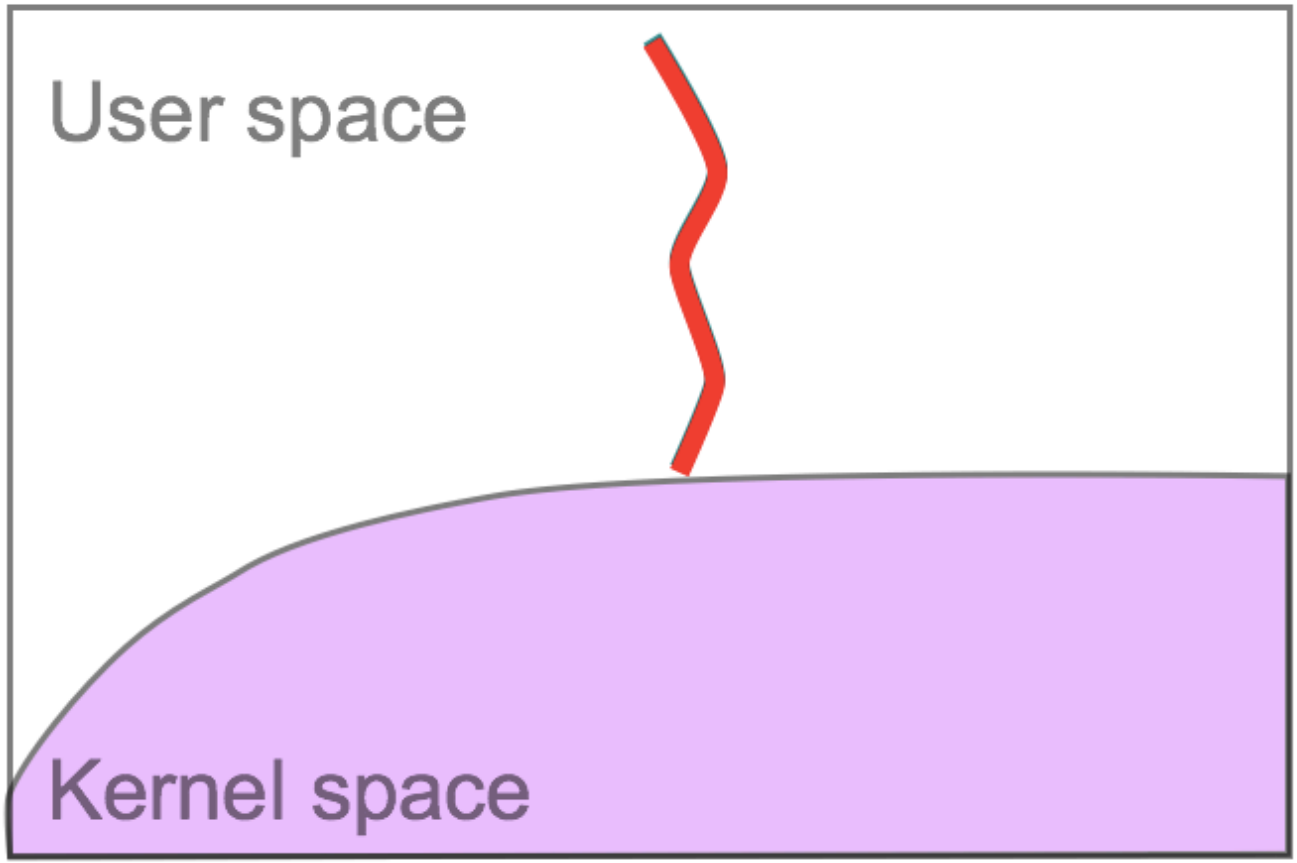
Multi-Path Performance Profiling

Single-Path Performance Profiling



Single-Path Performance Profiling



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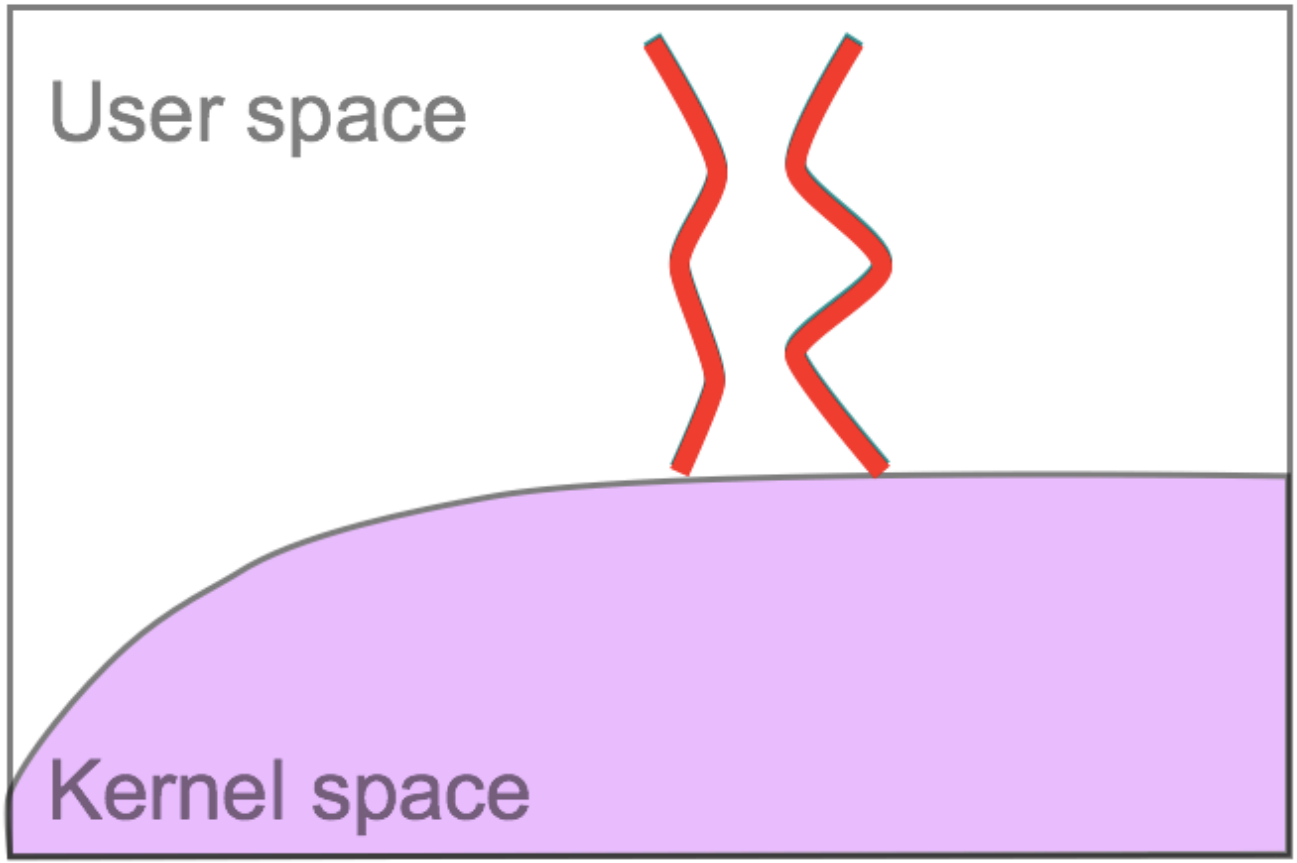

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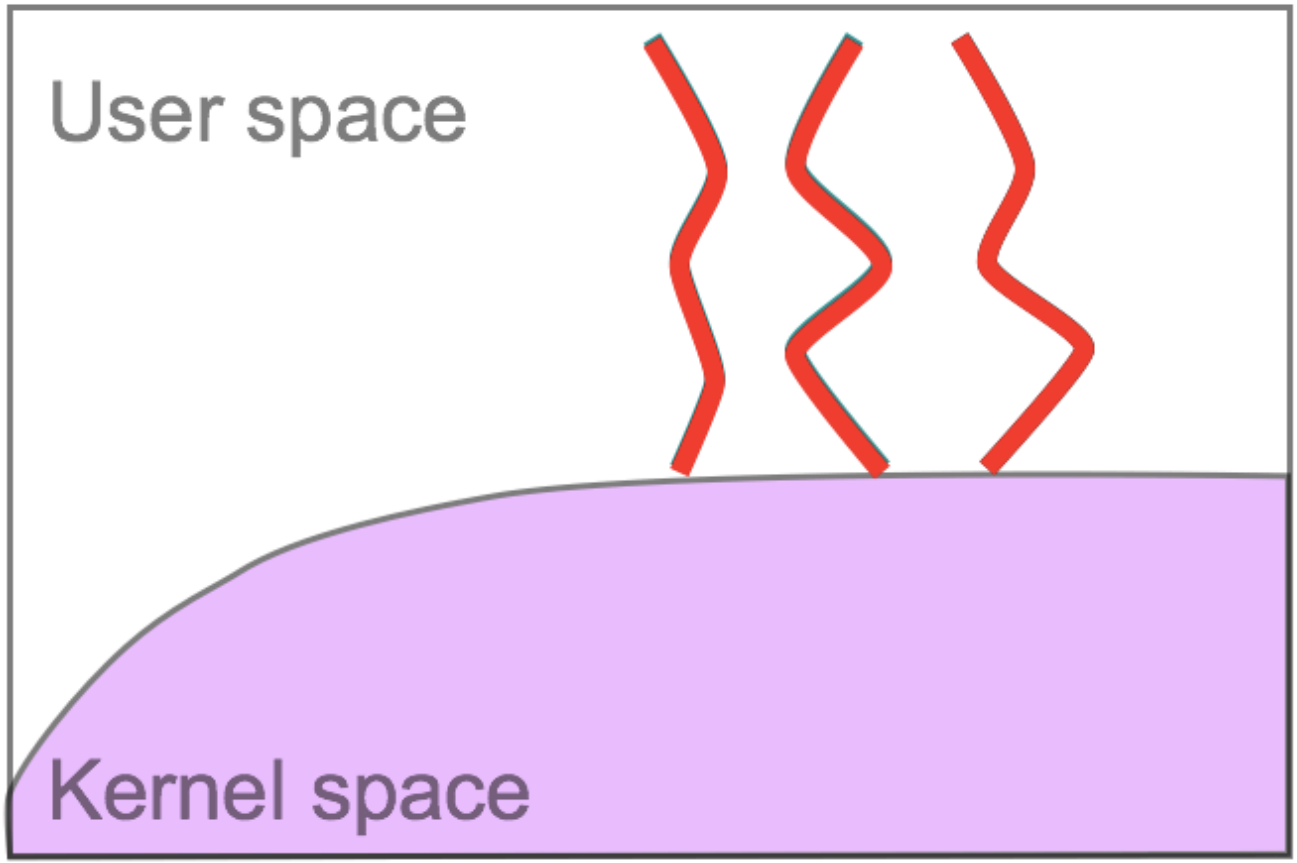
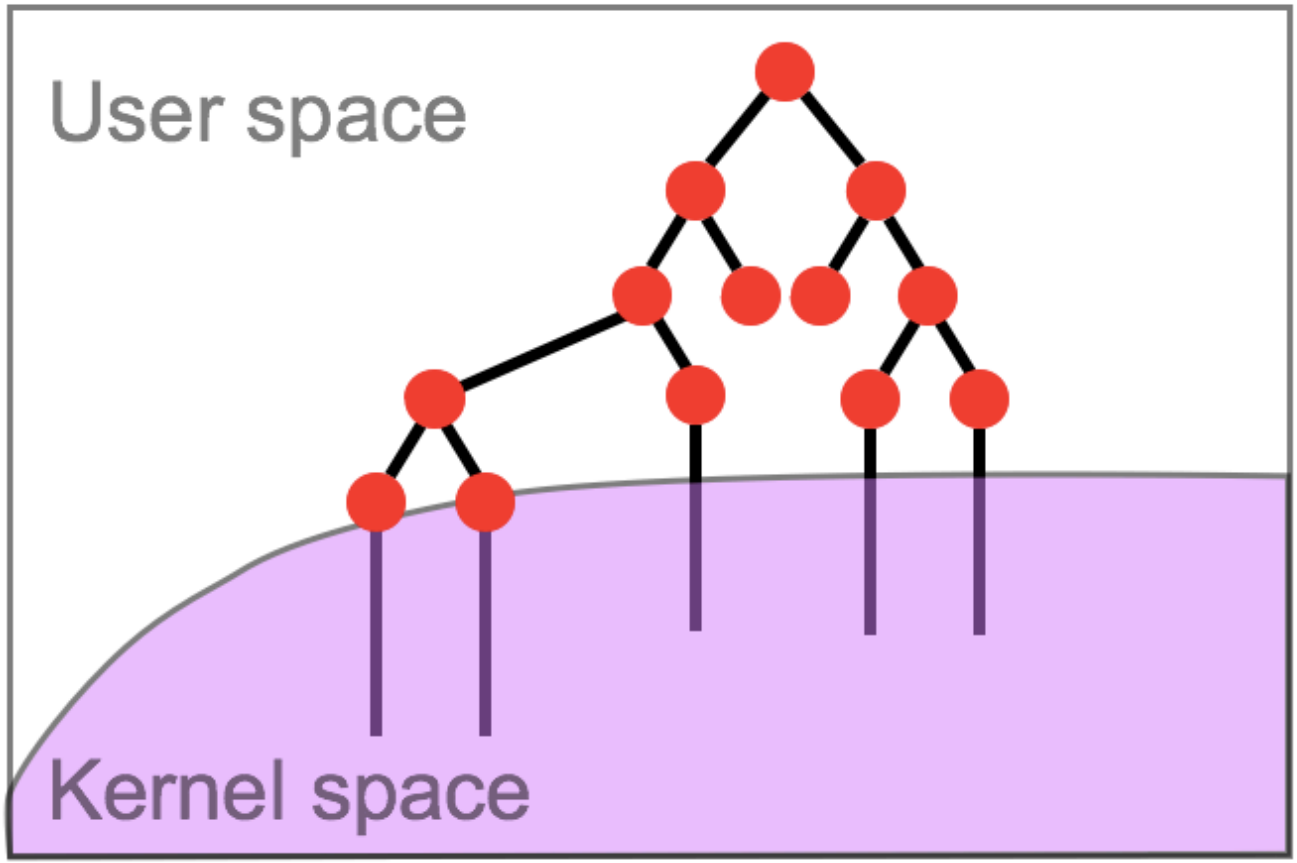
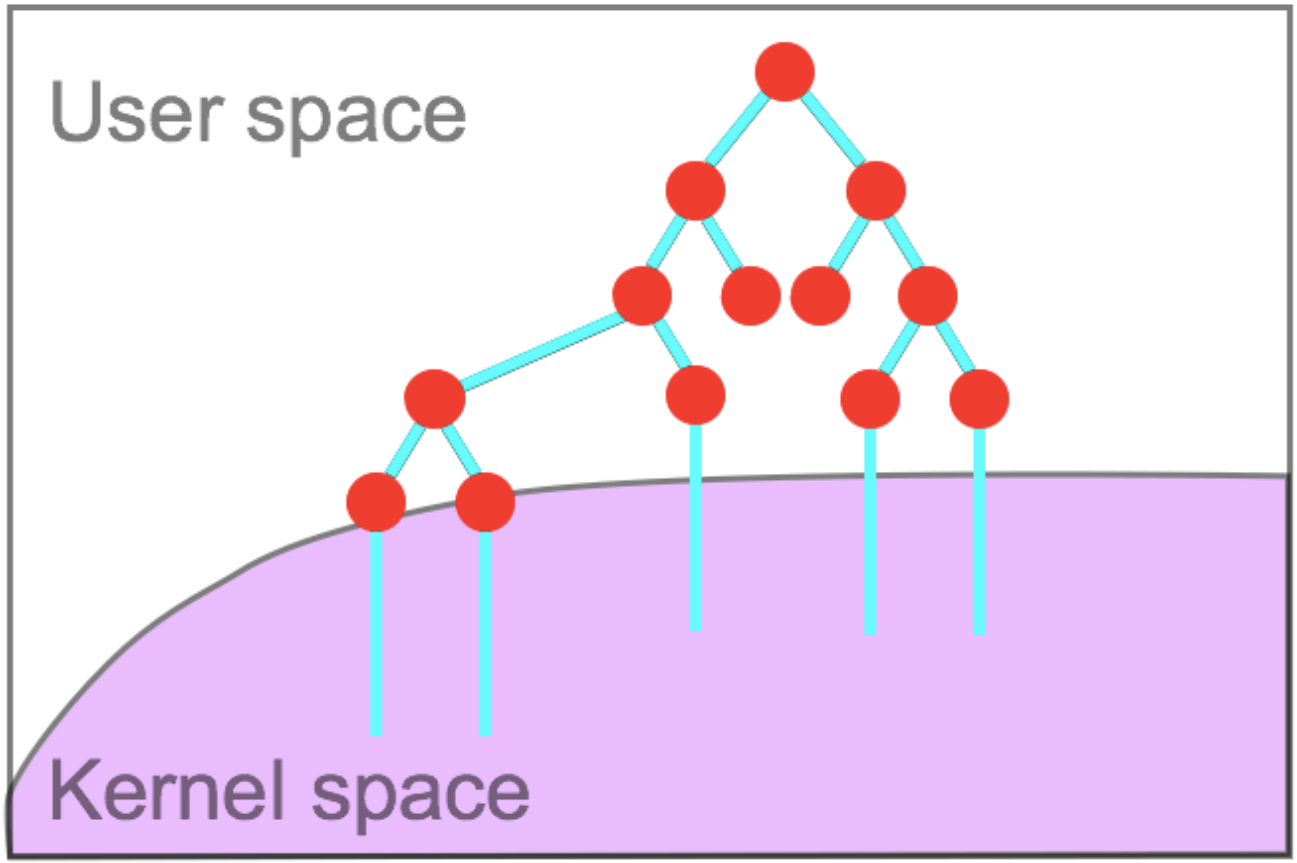


Multi-Path In-Vivo Profiling



Multi-Path In-Vivo Profiling



PROFs

- Cache Simulator
  Models arbitrary cache hierarchies
- Instruction Counter
  Machine instructions
- MMU Monitor
  Tracks TLB misses and page faults

Finding Performance Envelopes

- Upper and lower bound on performance
- Fastest and slowest execution path
- Metrics?
  - # instructions, cache misses, page faults, ...

Finding Performance Envelopes

ping

Finding Performance Envelopes

ping

Finding Performance Envelopes

ping

Finding Performance Envelopes

ping

>1.5 million instructions

Finding Performance Envelopes

ping

- Unbounded instruction count
- Infinite loop bug

>1.5 million instructions

Infinite Loop in Ping

```
void process_options(optptr...) {
  …
  while (totlen > 0) {
    …
    opt = optptr;
    …
    switch (*opt) {
      case OPTION_ROUTE_RECORD:
        length = *++opt;

        if (length < 4)
          continue;
    }
    …
  }
}
```

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```
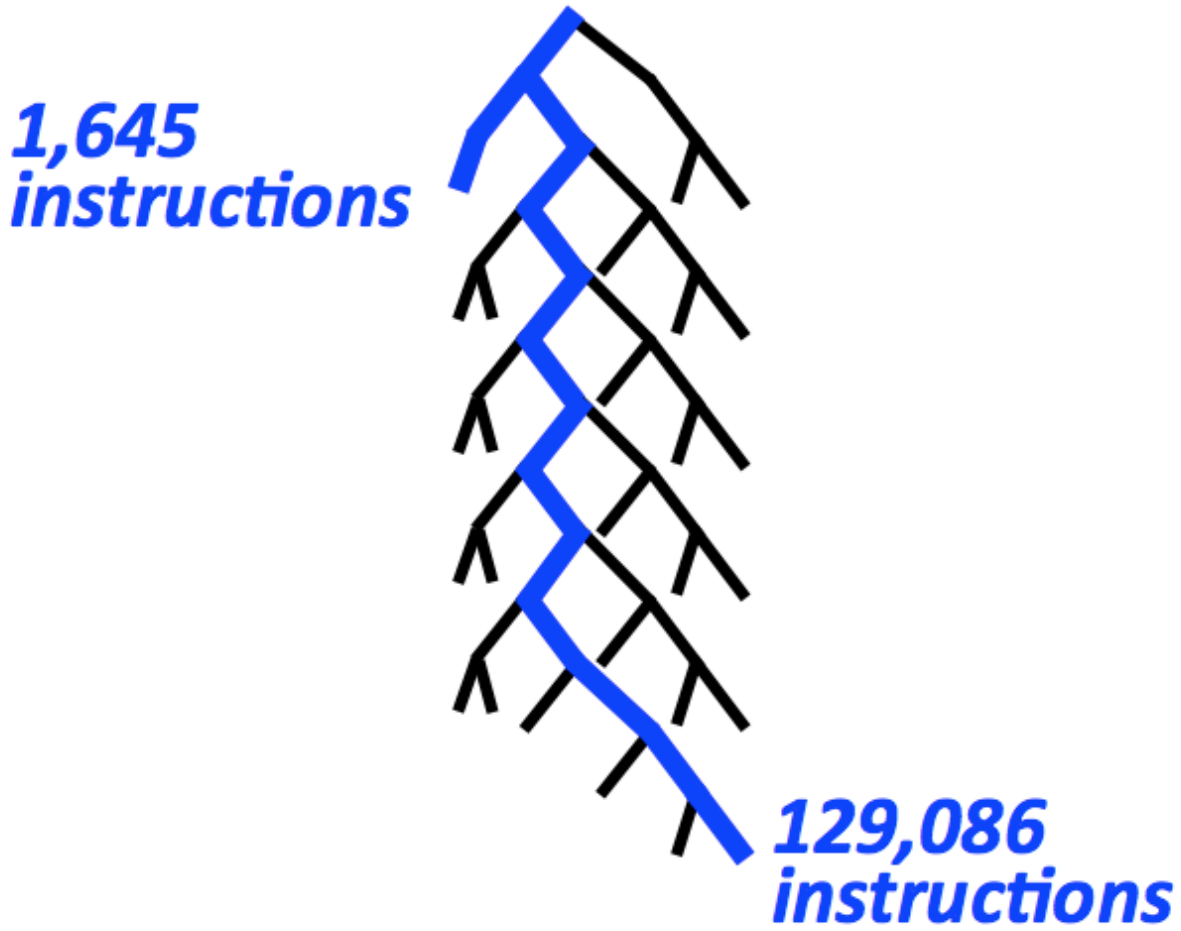

Perf. Envelope for Patched Ping

Perf. Envelope for Patched Ping



Other Uses of S2E

- Reverse engineering [Eurosys'10]
- Automated closed-source driver testing [USENIX'10]
- File system corruption impact analysis
  University of Wisconsin-Madison
- Symbolic execution of sensor networks
  RWTH Aachen University
- File system equivalence checking
  Max Planck Institute for Software Systems
- Energy profiling, privacy analysis, ...

Conclusion

- Execution consistency models
- Platform for in-vivo multi-path analysis
- Use of symbolic execution in performance analysis

http://s2e.epfl.ch

Ready-for-use VM, demos, tutorials, source code, documentation