Testing Noninterference, Quickly

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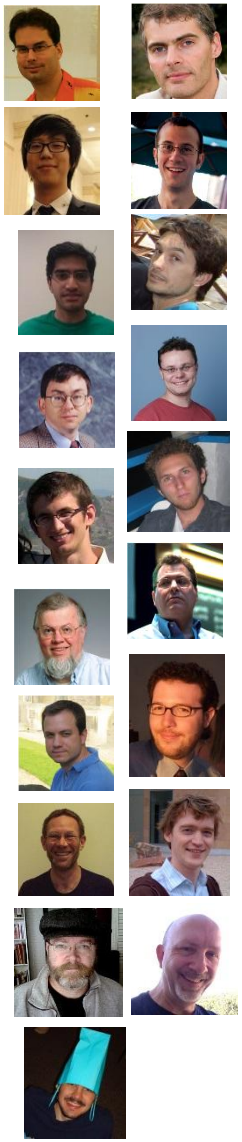
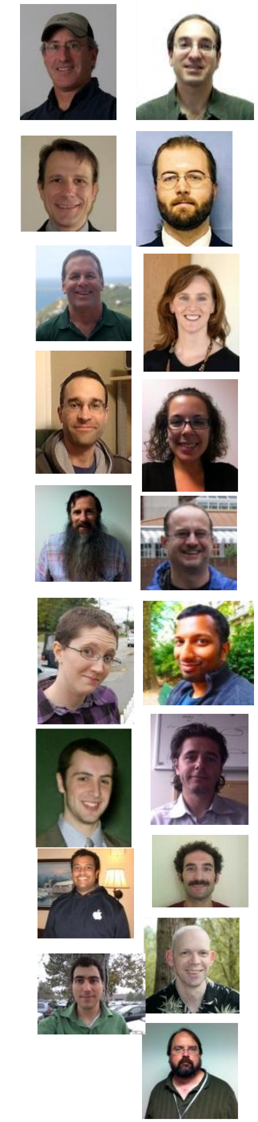
CRASH/SAFE project



- Academic partners (16):
  - **University of Pennsylvania** (11)
  - **Harvard University** (4)
  - **Northeastern University** (1)
- Industrial partners (24):
  - **BAE systems** (21) + **Clozure** (3)

} 40!

- Funded by DARPA
  - **C**lean-Slate Design of **R**esilient, **A**daptive, **S**ecure **H**osts



Clean-slate co-design of net host

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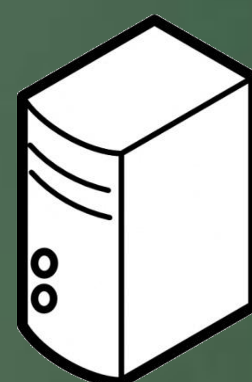
Primary goal:
design and implement a significantly more secure architecture, without backwards compatibility concerns



Clean-slate co-design of net host

Primary goal:
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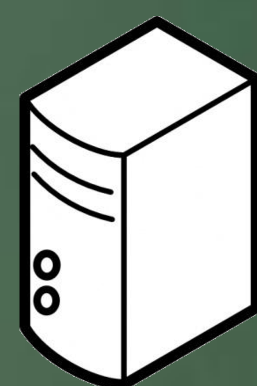
New stack:

- language
- system
- hardware



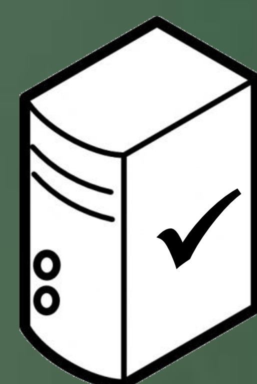
Clean-slate co-design of net host

Primary goal:
design and implement a significantly more secure architecture, without backwards compatibility concerns

Secondary goal:
verify that it's secure (whatever that means)

New stack:

- language
- system ✓
- hardware



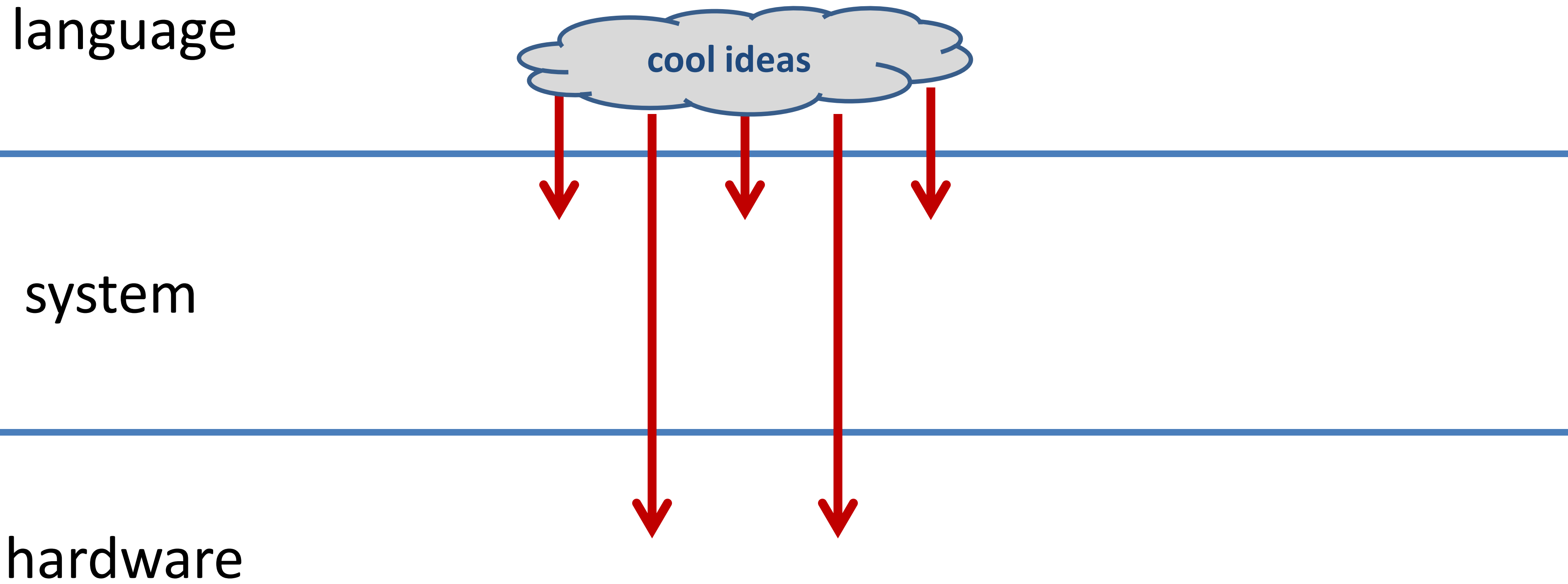
Design targeting security

language

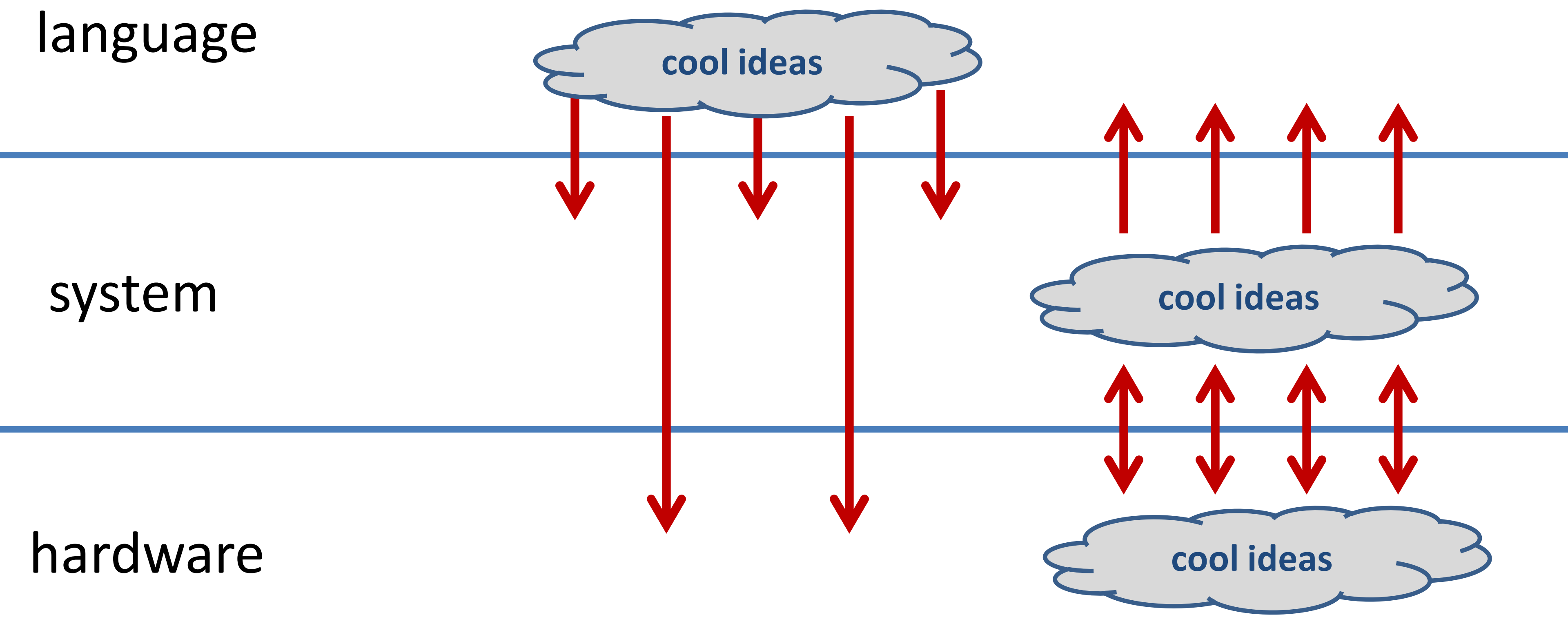
system

hardware

Design targeting security



Design targeting security



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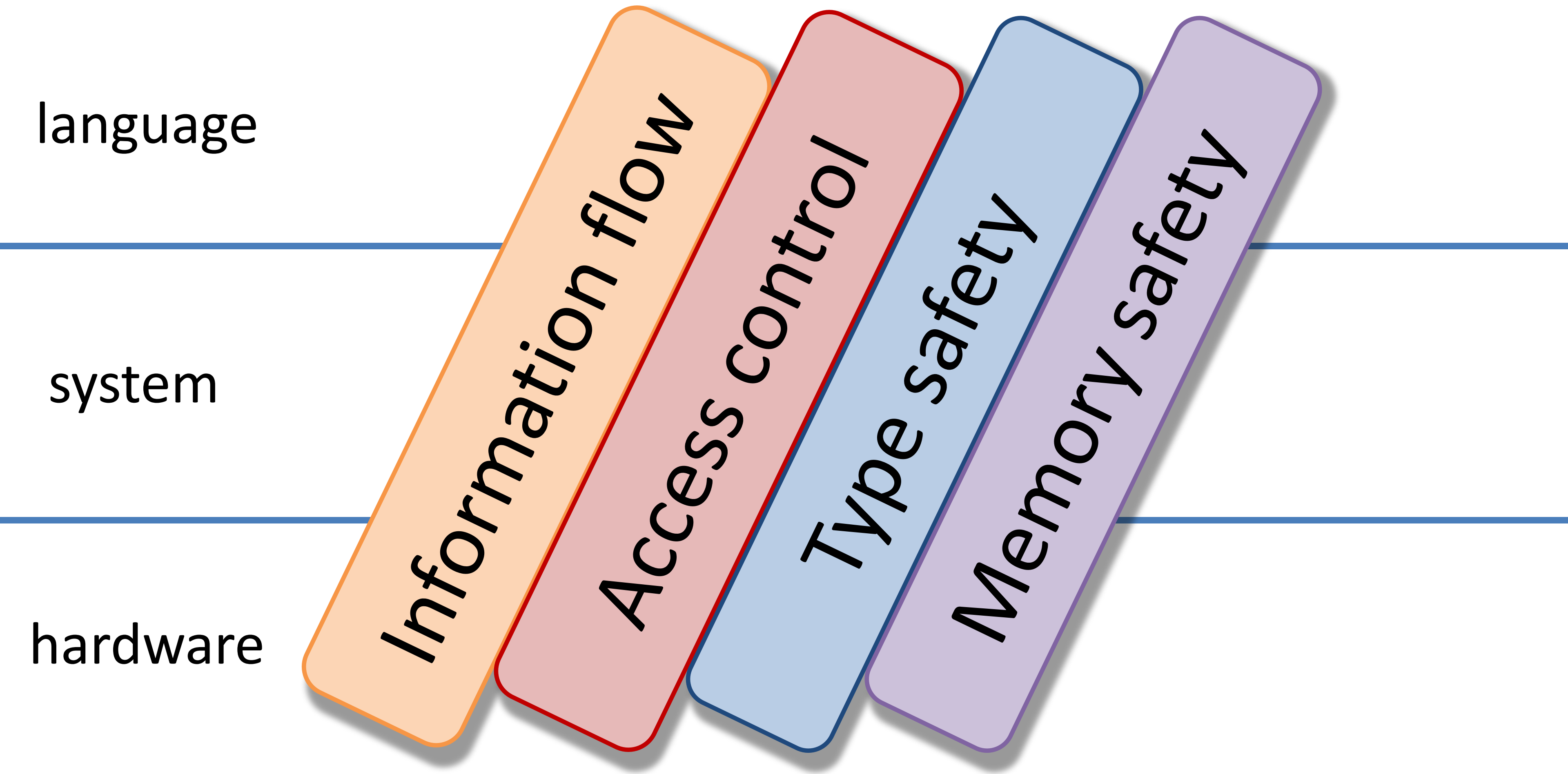
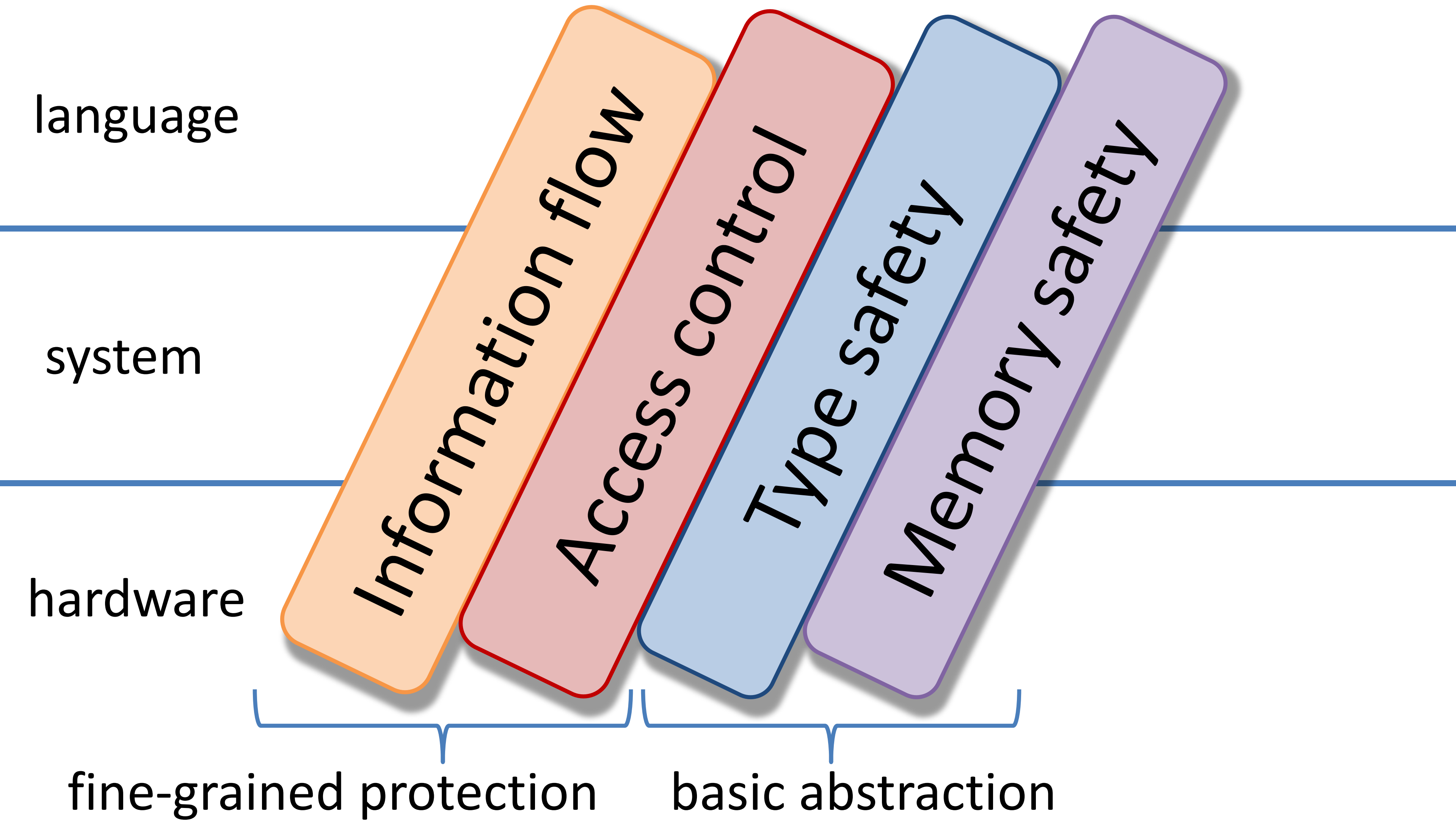


Design targeting security



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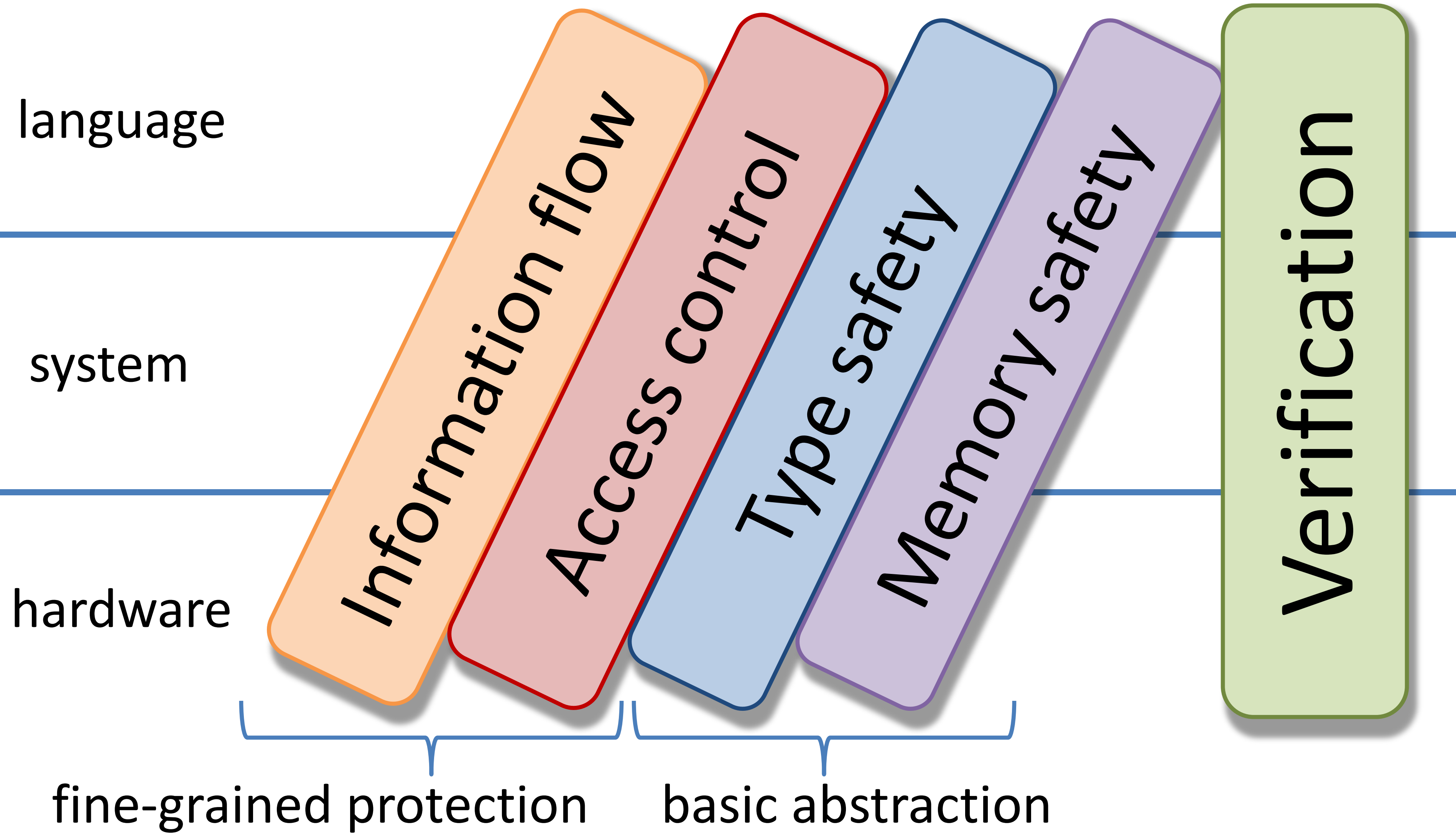

This talk

show how
property-based random testing
can aid design *and serve as*
a first step towards verification

Information flow

Verification

COUNTEREXAMPLE-GUIDED INFORMATION FLOW MACHINE DESIGN

A *very!* simple stack-and-memory machine

- values = integers
- stack = list of values
- memory = list of values

instruction	stack before	stack after	memory
Push n	stk	n : stk	
Pop	n : stk	stk	
Add	n : m : stk	(n+m) : stk	
Load	a : stk	mem[a] : stk	
Store	a : n : stk	stk	mem[a] := n
Halt	stk	----	

A *very!* simple information-flow machine

- values = labeled integers
- stack = list of values
- labels = L and H
- memory = list of values

instruction	stack before	stack after	memory
Push n@X	stk	n@X : stk	
Pop	n@X : stk	stk	
Add	n@X : m@Y :stk	(n+m)@? : stk	
Load	a@X : stk	mem[a] : stk	
Store	a@X : n@Y : stk	stk	mem[a] := n@?
Halt	stk	----	

A ~~very!~~ simple ~~wrong~~ information-flow machine

- values = labeled integers
- labels = L and H
- stack = list of values
- memory = list of values

instruction	stack before	stack after	memory
Push n@X	stk	n@X : stk	
Pop	n@X : stk	stk	
Add	n@X : m@Y :stk	(n+m)@L : stk	
Load	a@X : stk	mem[a] : stk	
Store	a@X : n@Y : stk	stk	mem[a] := n@L
Halt	stk	----	

Noninterference (EENI)

- “secret inputs don’t affect public outputs”
  - secret inputs = numbers labeled H in initial state
    - initial state = empty stack, memory all 0@L, instructions can contain secrets (Push 0@H)
  - public outputs = memory labeled L in halted state

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- more precisely:
  - forall i_1 i_2, if $i_1 \approx i_2$ and $i_1 \rightarrow^* h_1$ and $i_2 \rightarrow^* h_2$ then $mem(h_1) \approx mem(h_2)$

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  - $n_1@L \approx n_2@L$ iff $n_1 = n_2$ $\quad$ $n_1@H \approx n_2@H$ always

READY TO SQUASH SOME BUGS?

(let’s assume we have a property-based random testing framework in place)

Counterexample #1

memory	stack	next instruction
[0@L]	[]	Push {0/1}@H
[0@L]	[{0/1}@H]	Push 0@L
[0@L]	[0@L,{0/1}@H]	Store
[{0/1}@L]	[]	Halt

Counterexample #1

memory	stack	next instruction
[0@L]	[]	Push {0/1}@H
[0@L]	[{0/1}@H]	Push 0@L
[0@L]	[0@L,{0/1}@H]	Store
[{0/1}@L]	[]	Halt

Counterexample #1

memory	stack	next instruction
[0@L]	[]	Push {0/1}@H
[0@L]	[{0/1}@H]	Push 0@L
[0@L]	[0@L,{0/1}@H]	Store
[{0/1}@L]	[]	Halt

Fixing bug in Store

instruction	stack before	stack after	memory
Store	a@X : n@Y : stk	stk	mem[a] := n@Y

Counterexample #2

memory	stack	next instruction
[0@L,0@L]	[]	Push 1@L
[0@L,0@L]	[1@L]	Push {0/1}@H
[0@L,0@L]	[{0/1}@H,1@L]	Store
[{1/0}@L,{0/1}@L]	[]	Halt

Counterexample #2

memory	stack	next instruction
[0@L,0@L]	[]	Push 1@L
[0@L,0@L]	[1@L]	Push {0/1}@H
[0@L,0@L]	[{0/1}@H,1@L]	Store
[{1/0}@L,{0/1}@L]	[]	Halt

Counterexample #2

memory	stack	next instruction
[0@L,0@L]	[]	Push 1@L
[0@L,0@L]	[1@L]	Push {0/1}@H
[0@L,0@L]	[{0/1}@H,1@L]	Store
[{1/0}@L,{0/1}@L]	[]	Halt

Fixing 2nd bug in Store

instruction	stack before	stack after	memory
Store	a@X : n@Y : stk	stk	mem[a] := n@$X \sqcup Y$

Counterexample #3

memory	stack	next instruction
[0@L,0@L]	[]	Push **1**@L
[0@L,0@L]	[0@L]	Push {0/1}@H
[0@L,0@L]	[{0/1}@H,**1**@L]	Store
[{**1**@H/0@L},{0@L/**1**@H}]	[]	Halt

Counterexample #3

memory	stack	next instruction
[0@L,0@L]	[]	Push **1**@L
[0@L,0@L]	[0@L]	Push {0/1}@H
[0@L,0@L]	[{0/1}@H,**1**@L]	Store
[{**1**@H/0@L},{0@L/**1**@H}]	[]	Halt

Counterexample #3

memory	stack	next instruction
[0@L,0@L]	[]	Push **1**@L
[0@L,0@L]	[0@L]	Push {0/1}@H
[0@L,0@L]	[{0/1}@H,**1**@L]	Store
[{**1**@H/0@L},{0@L/**1**@H}]	[]	Halt

Fixing 3rd bug in Store

stack before	side condition	stack after	memory
a@X : n@Y : stk	Y ≤ labOf(mem[a])	stk	mem[a] := n@X⊔Y

No sensitive upgrade [Steve Zdancewic's PhD, 2002]

Counterexample #3

memory	stack	next instruction
[0@L,0@L]	[]	Push **1**@L
[0@L,0@L]	[0@L]	Push {0/1}@H
[0@L,0@L]	[{0/1}@H,**1**@L]	Store
[{**1**@H/0@L},{0@L/**1**@H}]	[]	Halt

Fixing 3nd bug in Store

stack before	side condition	stack after	memory
a@X : n@Y : stk	Y ≤ labOf(mem[a])	stk	mem[a] := n@X⊔Y

No sensitive upgrade [Steve Zdancewic's PhD, 2002]

*the real counterexample had Push **0**@L as the first instruction

Counterexample #4

memory	stack	next instruction
[0@L]	[]	Push 0@L
[0@L]	[0@L]	Push {0/1}@H
[0@L]	[{0/1}@H,0@L]	Add
[0@L]	[{0/1}@L]	Push 0@L
[0@L]	[0@L,{0/1}@L]	Store
[{0/1}@L]	[]	Halt

Counterexample #4

memory	stack	next instruction
[0@L]	[]	Push 0@L
[0@L]	[0@L]	Push {0/1}@H
[0@L]	[{0/1}@H,0@L]	Add
[0@L]	[{0/1}@L]	Push 0@L
[0@L]	[0@L,{0/1}@L]	Store
[{0/1}@L]	[]	Halt

Counterexample #4

memory	stack	next instruction
[0@L]	[]	Push 0@L
[0@L]	[0@L]	Push {0/1}@H
[0@L]	[{0/1}@H,0@L]	Add
[0@L]	[{0/1}@L]	Push 0@L
[0@L]	[0@L,{0/1}@L]	Store
[{0/1}@L]	[]	Halt

Fixing bug in Add

instruction	stack before	stack after	memory
Add	n@X : m@Y :stk	(n+m)@(X⊔Y) : stk	

Counterexample #5

memory	stack	next instruction
[0@L,0@L]	[]	Push 1@L
[0@L,0@L]	[1@L]	Push 0@L
[0@L,0@L]	[0@L,1@L]	Store
[1@L,0@L]	[]	Push {1/0}@H
[1@L,0@L]	[{1/0}@H]	Load
[1@L,0@L]	[{0/1}@L]	Push 0@L
[1@L,0@L]	[0@L,{0/1}@L]	Store
[{0/1}@L,0@L]	[]	Halt

Counterexample #5

memory	stack	next instruction
[0@L,0@L]	[]	Push 1@L
[0@L,0@L]	[1@L]	Push 0@L
[0@L,0@L]	[0@L,1@L]	Store
[1@L,0@L]	[]	Push {1/0}@H
[1@L,0@L]	[{1/0}@H]	Load
[1@L,0@L]	[{0/1}@L]	Push 0@L
[1@L,0@L]	[0@L,{0/1}@L]	Store
[{0/1}@L,0@L]	[]	Halt

Counterexample #5

memory	stack	next instruction
[0@L,0@L]	[]	Push 1@L
[0@L,0@L]	[1@L]	Push 0@L
[0@L,0@L]	[0@L,1@L]	Store
[1@L,0@L]	[]	Push {1/0}@H
[1@L,0@L]	[{1/0}@H]	Load
[1@L,0@L]	[{0/1}@L]	Push 0@L
[1@L,0@L]	[0@L,{0/1}@L]	Store
[{0/1}@L,0@L]	[]	Halt

Fixing bug in Load

instruction	stack before	stack after	memory
Load	a@X : stk	mem[a]@X : stk	

HOW DID WE DO THIS?

Main ingredients

- QuickCheck
- Rephrasing preconditions
- Clever program generation strategies
- Shrinking counterexamples
- Later one more: stronger properties

QuickCheck [Claessen & Hughes, ICFP 2000]

- Property-based random testing tool for Haskell
- Property ~= Boolean Haskell expression
  - QC generates random instances for variables
  - implications treated a bit specially
    - failing precondition counted as “discard”
- Default random generators using type-classes
  - uniformly at random

QuickCheck [Claessen & Hughes, ICFP 2000]

- Property-based random testing tool for Haskell
- Property ~= Boolean Haskell expression
  - QC generates random instances for variables
  - implications treated a bit specially
    - failing precondition counted as “discard”
- Default random generators using type-classes
  - uniformly at random
- Out of the box it doesn't work for us! ☹
  - couldn’t find any bug; astronomic discard rate

(Re)phrasing noninterference

Original ☹

for random i_1,
for random i_2,
  if $i_1 \approx i_2$ ← **Rare**
    and $i_1 \longrightarrow^* h_1$
    and $i_2 \longrightarrow^* h_2$
  then
    $mem(h_1) \approx mem(h_2)$

(Re)phrasing noninterference

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  then
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Much better ☺

for random i_1,
for random
  $\approx$ variation i_2 of i_1,
  if $i_1 \to^* h_1$
    and $i_2 \to^* h_2$
  then
    $mem(h_1) \approx mem(h_2)$

- How can we evaluate how good our testing is?
  – add bugs one at a time and see how fast they're found
  – Mean Time to Find (MTTF)

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	Bug	MTTF
from before	1^{nd} for Store	8s
from before	2^{st} for Store	∞*
from before	3^{rd} for Store	47s
from before	Add	83s
from before	Load	∞*
new	Push	4s

*not found in 300s

Naive generation

- How can we evaluate how ~~good~~ bad our testing is?
  - add bugs one at a time and see how fast they're found
  - Mean Time to Find (MTTF)

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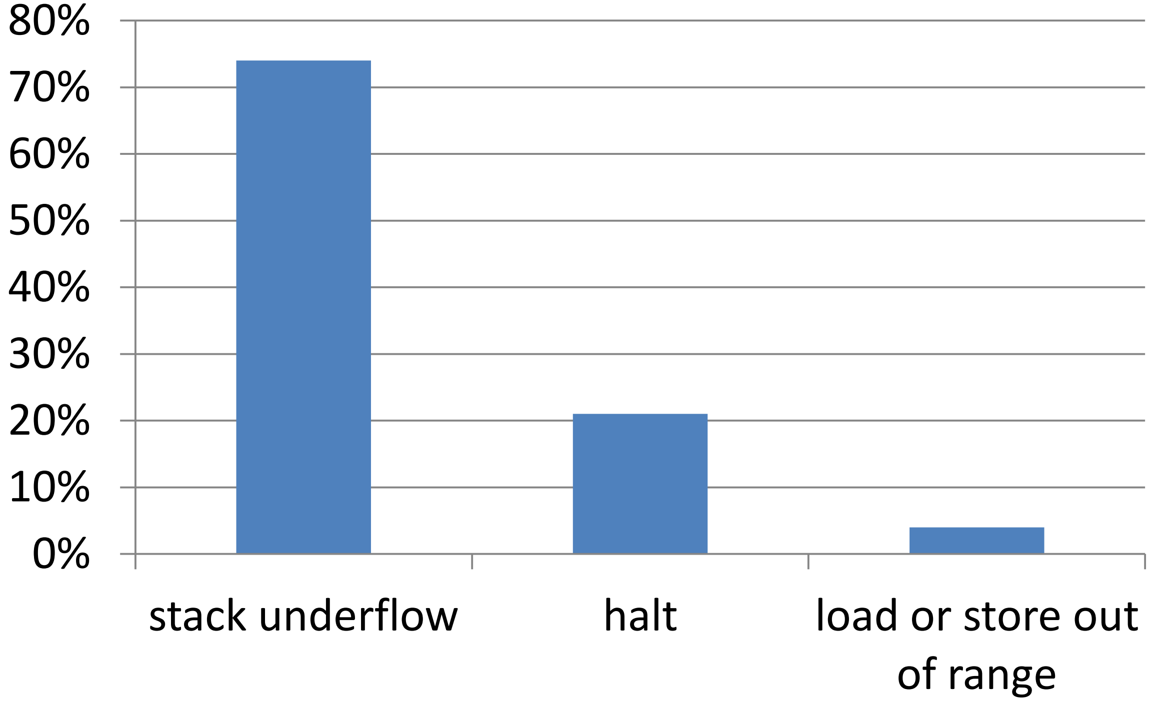
new	Push	4s

*not found in 300s

Some statistics

- new discard rate: 79%
- average number of execution steps: 0.47
- reasons for termination

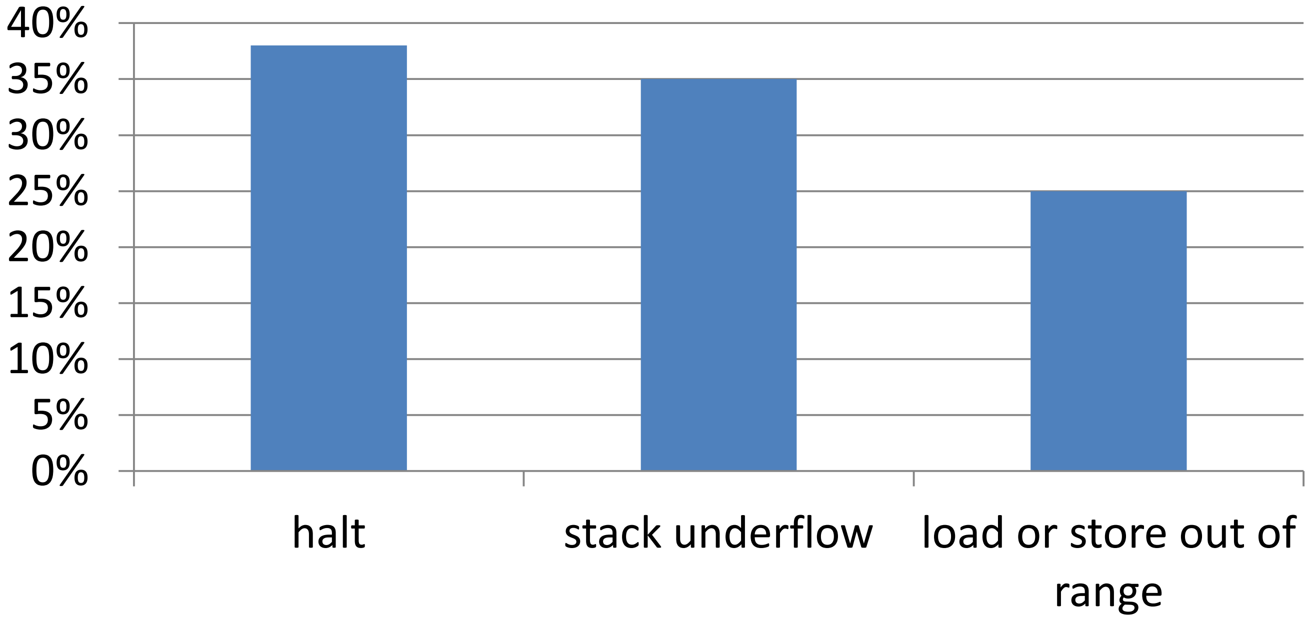


Weighted distribution on instructions

- increased chance of getting Push or Halt

Weighted distribution on instructions

- increased chance of getting Push or Halt
- average number of execution steps: 2.69
- reasons for termination

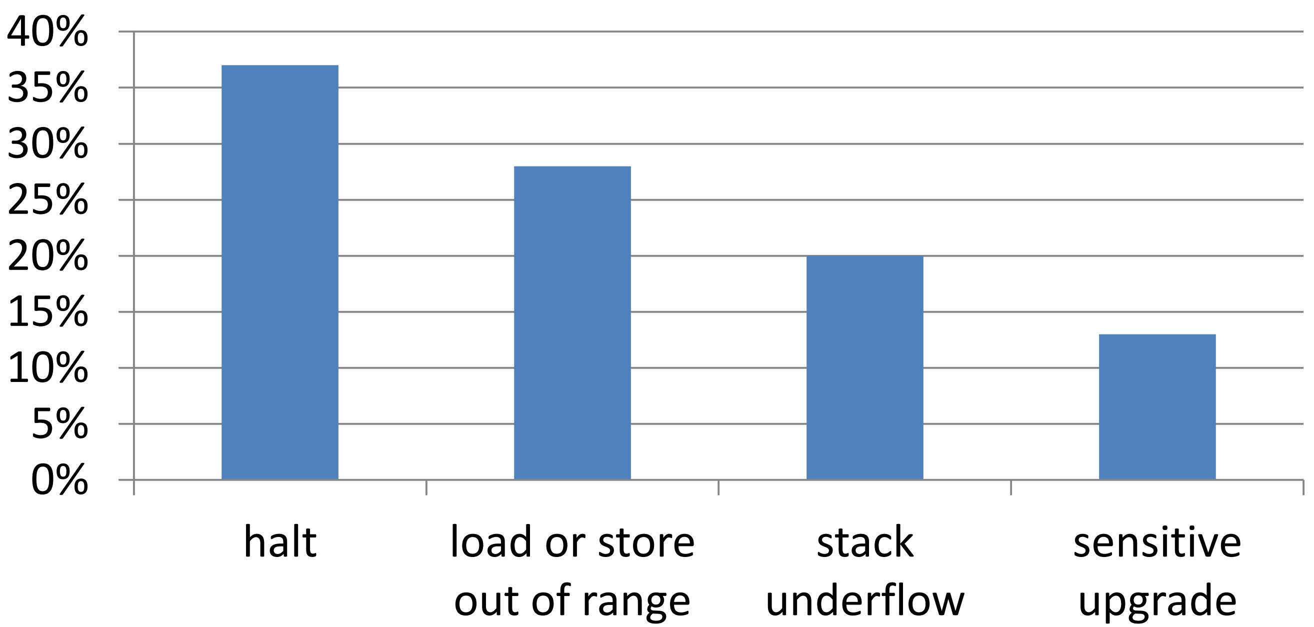


Instruction sequences

- generating useful instruction sequences more often (e.g. Push a; Store, where a is valid addr)

Instruction sequences

- generating useful instruction sequences more often (e.g. Push a; Store, where a is valid addr)
- average number of execution steps: 3.86
- reasons for termination

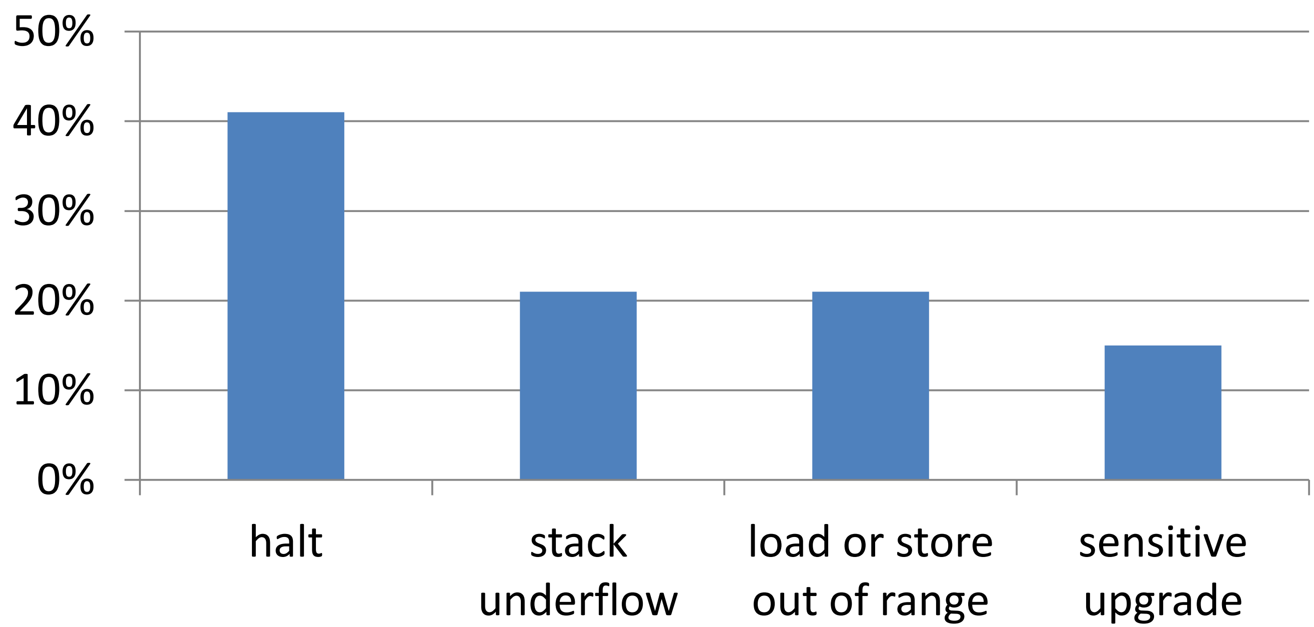


Smart integers

- generating valid code and data addr. more often
  - varying valid addr with high probability to other addr

Smart integers

- generating valid code and data addr. more often
  - varying valid addr with high probability to other addr
- average number of execution steps: 4.22
- reasons for termination



They don't just run longer ...

- Smarter generation finds bugs much faster
- Mean Time to Find (MTTF)

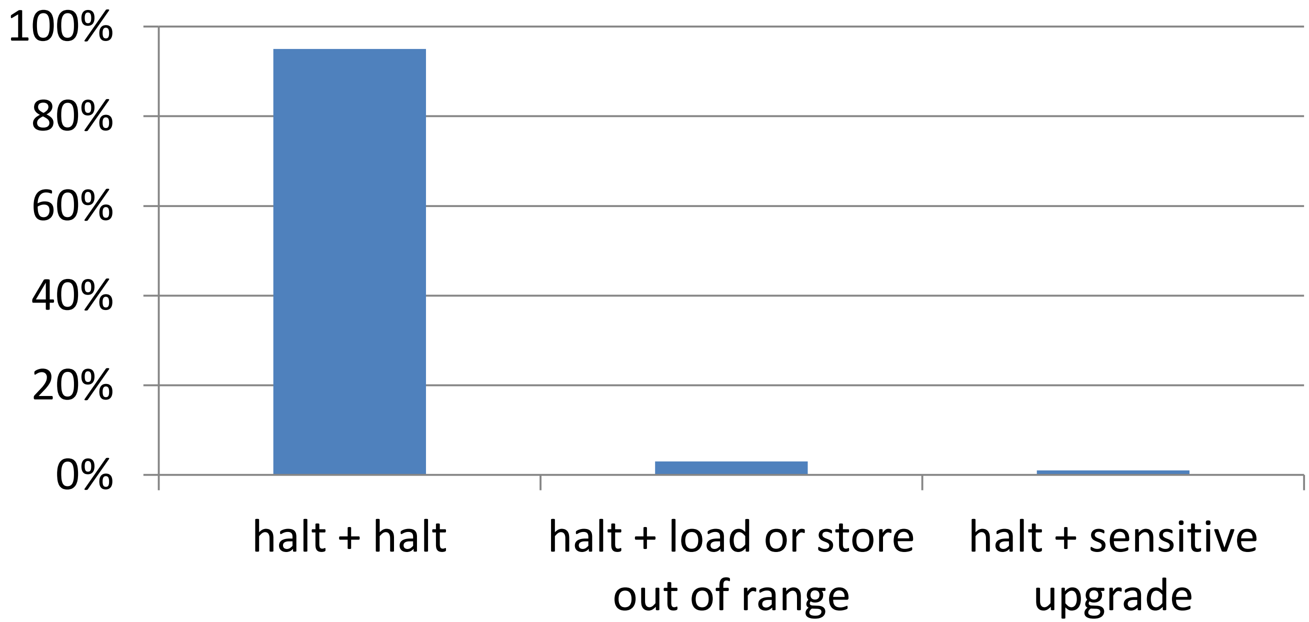
Bug	Naive	Smarter
1^{st} for Store	7660.07ms	0.31ms
2^{nd} for Store	∞	32227.10ms
3^{rd} for Store	47365.97ms	0.12ms
Add	83247.01ms	30.05ms
Load	∞	2258.93ms
Push	3552.54ms	0.07ms

Generation by execution

- try to generate instruction seq that doesn't crash
- maintain a current state
  - generate instr(s) that make sense in current state
  - run instr(s) to obtain new current state
  - fully precise for straight-line code
- jumps forward easy, jumps backward harder
  - look ahead 2 steps before committing to jump
  - current state still not always accurate
- give Halt more weight as execution gets longer

Statistics for generation by execution

- average number of execution steps:
  - 11.6 for original program, 11.26 for variation
- reasons for termination (original + variation)



Generation by execution finds bugs faster

Bug	Naive	Smarter	By Exec	
1st for Store	7660.07ms	0.31ms	0.02ms	
2nd for Store	∞	32227.10ms	1233.51ms	
3rd for Store	47365.97ms	0.12ms	0.25ms	
Add	83247.01ms	30.05ms	0.87ms	
Load	∞	2258.93ms	4.03ms	
Push	3552.54ms	0.07ms	0.01ms	
Arith. mean	∞	5752.76ms	206.45ms	28x
Geom. mean	∞	13.33ms	0.77ms	17x
tests / second	24129	7915	3284	
discard rate	79%	59%	4%	

Adding control flow

- jumps & procedures
  - machine more interesting from IFC pov
- stack also serves as call stack
- 14 bugs = 6 old bugs + 8 new bugs
- GenByExec
  - finds 13 of them in 0.22ms to 69s
  - misses one completely:
    not protecting call stack is unsound

Counterexample to Load bug

takes 155ms to find now; 433 tests (average)

memory	stack	next instruction
[0@L,0@L]	[]	Push 1@L
[0@L,0@L]	[1@L]	Push 0@L
[0@L,0@L]	[0@L,1@L]	Store
[1@L,0@L]	[]	Push {1/0}@H
[1@L,0@L]	[{1/0}@H]	Load
[1@L,0@L]	[{0/1}@L]	Push 0@L
[1@L,0@L]	[0@L,{0/1}@L]	Store
[{0/1}@L,0@L]	[]	Halt

Counterexample to Load bug

takes 155ms to find now; 433 tests (average)

	memory	stack	next instruction
setting up	[0@L,0@L]	[]	Push 1@L
	[0@L,0@L]	[1@L]	Push 0@L
	[0@L,0@L]	[0@L,1@L]	Store
	[1@L,0@L]	[]	Push {1/0}@H
	[1@L,0@L]	[{1/0}@H]	Load ← bug
observing	[1@L,0@L]	[{0/1}@L]	Push 0@L
	[1@L,0@L]	[0@L,{0/1}@L]	Store
	[{0/1}@L,0@L]	[]	Halt

Stronger noninterference

Current ☹

for random i_1,

for random

≈ variation i_2 of i_1,

if $i_1 \longrightarrow^* h_1$

and $i_2 \longrightarrow^* h_2$

then

$mem(h_1) \approx mem(h_2)$

Stronger noninterference

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Better ☺

for random q_1,
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 ≈ variation q_2 of q_1,
 if $q_1 \rightarrow^* h_1$
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 then
  $h_1 \approx h_2$

Stronger noninterference

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Better ☺

for random q_1,
for random
 ≈ variation q_2 of q_1,
 if $q_1 \longrightarrow^* h_1$
  and $q_2 \longrightarrow^* h_2$
 then
  $h_1 \approx h_2$

q - quasi initial = arbitrary, but labOf(pc)≠H
(control not affected by secrets)

≈ equates all H states

Counterexamples to Load bug

used to take 155ms to find; 433 tests

now it takes 6ms to find; 12 tests (average)

memory	stack	next instruction
[0@L,1@L]	[]	Push {0/1}@H
[0@L,1@L]	[{0/1}@H]	Load
[0@L,1@L]	[{0/1}@L]	Halt

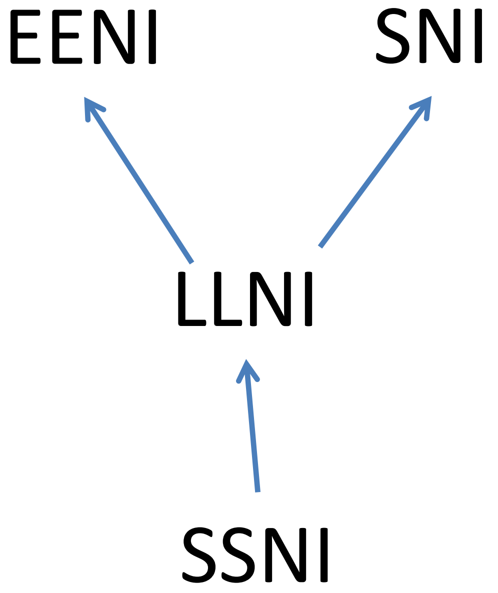
memory	stack	next instruction
[0@L,1@L]	[{1/0}@H]	Load
[0@L,1@L]	[{1/0}@L]	Halt

This finds all bugs, including ...

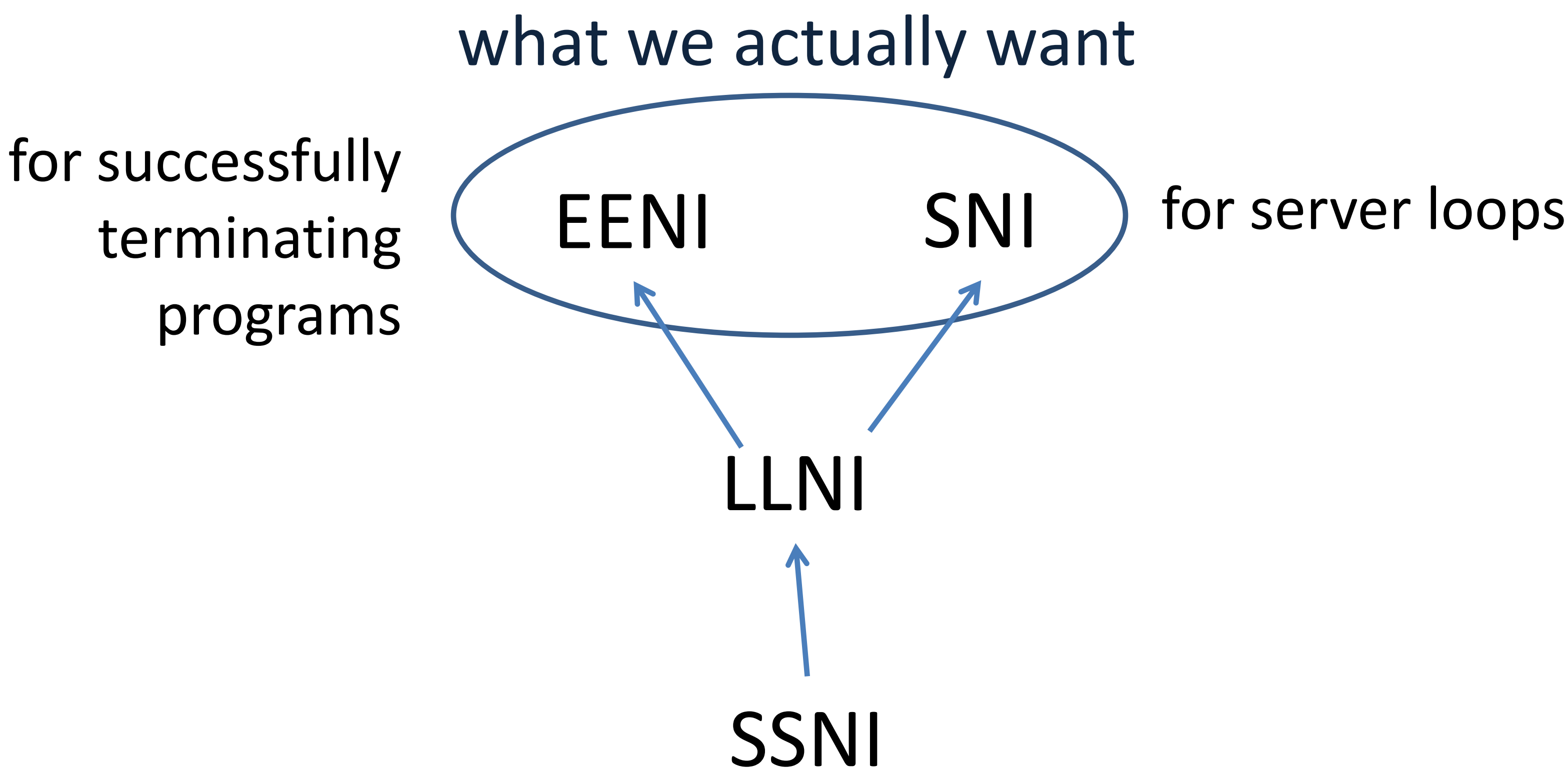
it takes 16s to find this one (average)

memory	stack	next instruction
[]	[ARet (3,False)@L,0@L,ARet (4,True)@L]	Push {3/2}@H
[]	[{3/2}@H,ARet (3,False)@L,0@L,ARet (4,True)@L]	Jump
execution 1 continues ...		
[]	[ARet (3,False)@L,0@L,ARet (4,True)@L]	Return False
[]	[0@L,ARet (4,True)@L]	Return False
[]	[0@L]	Halt
execution 2 continues ...		
[]	[ARet (3,False)@L,0@L,ARet (4,True)@L]	Pop
[]	[0@L,ARet (4,True)@L]	Return False
[]	[0@H]	Halt

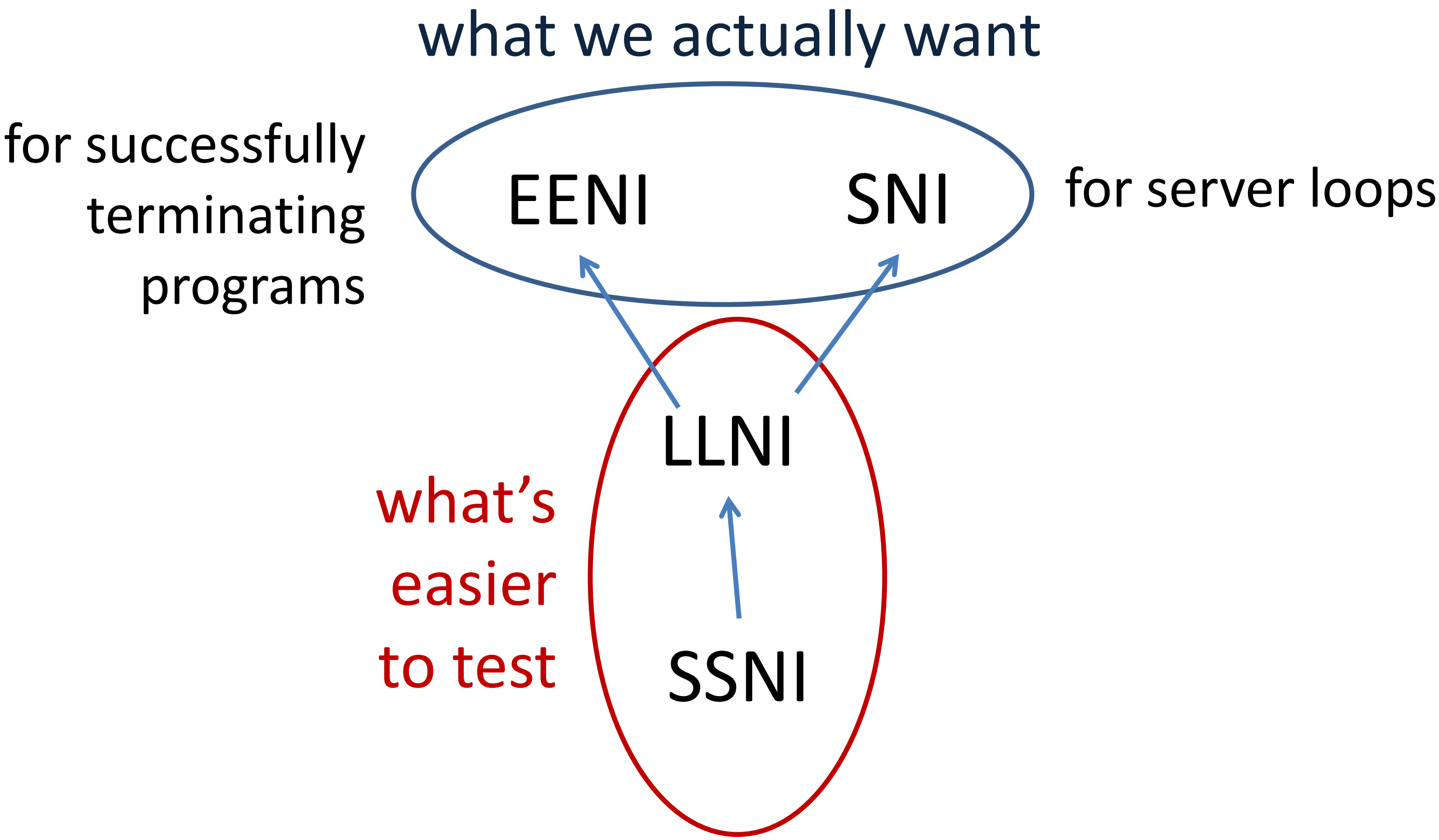
Even stronger noninterference



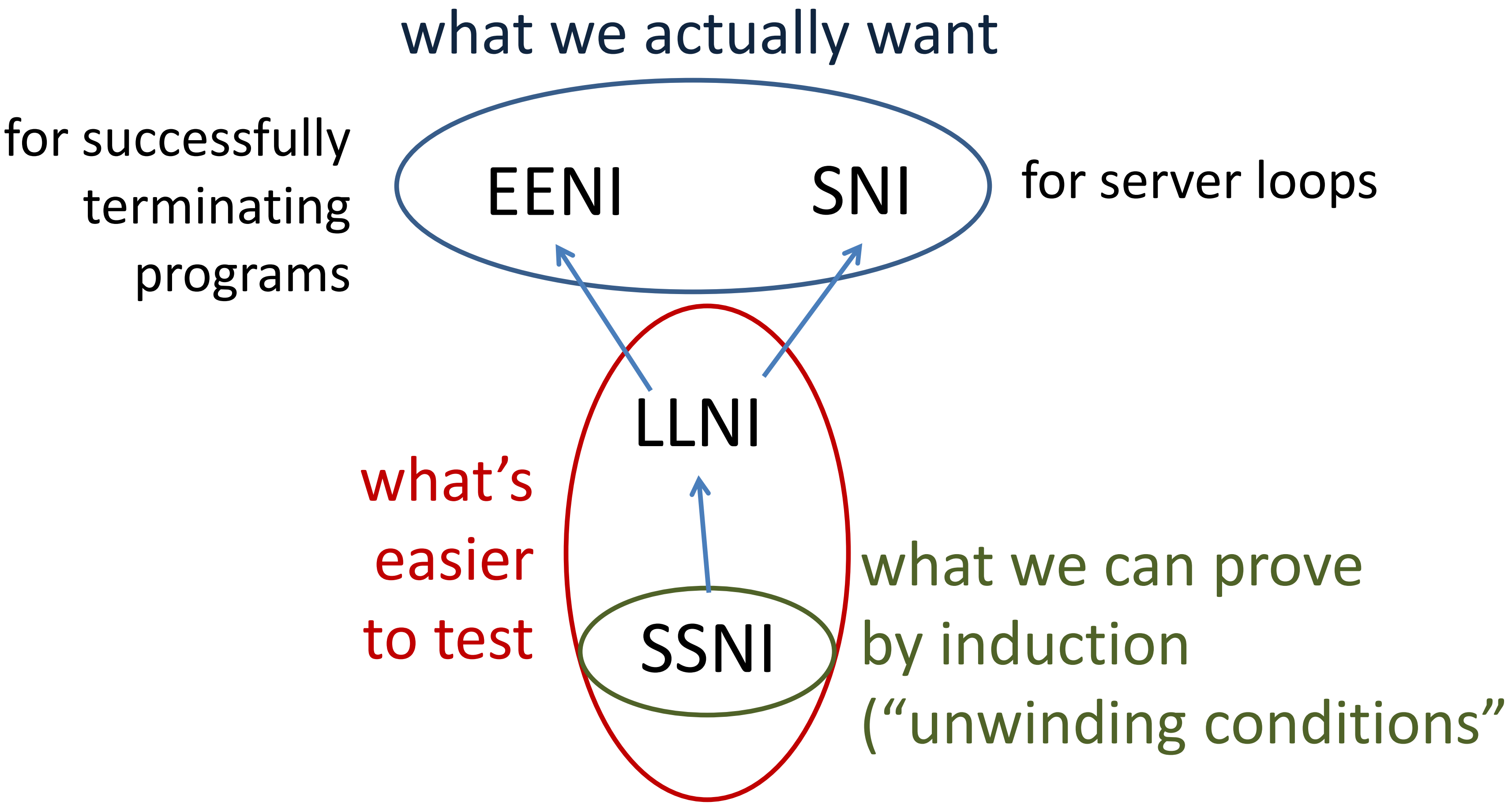
Even stronger noninterference



Even stronger noninterference

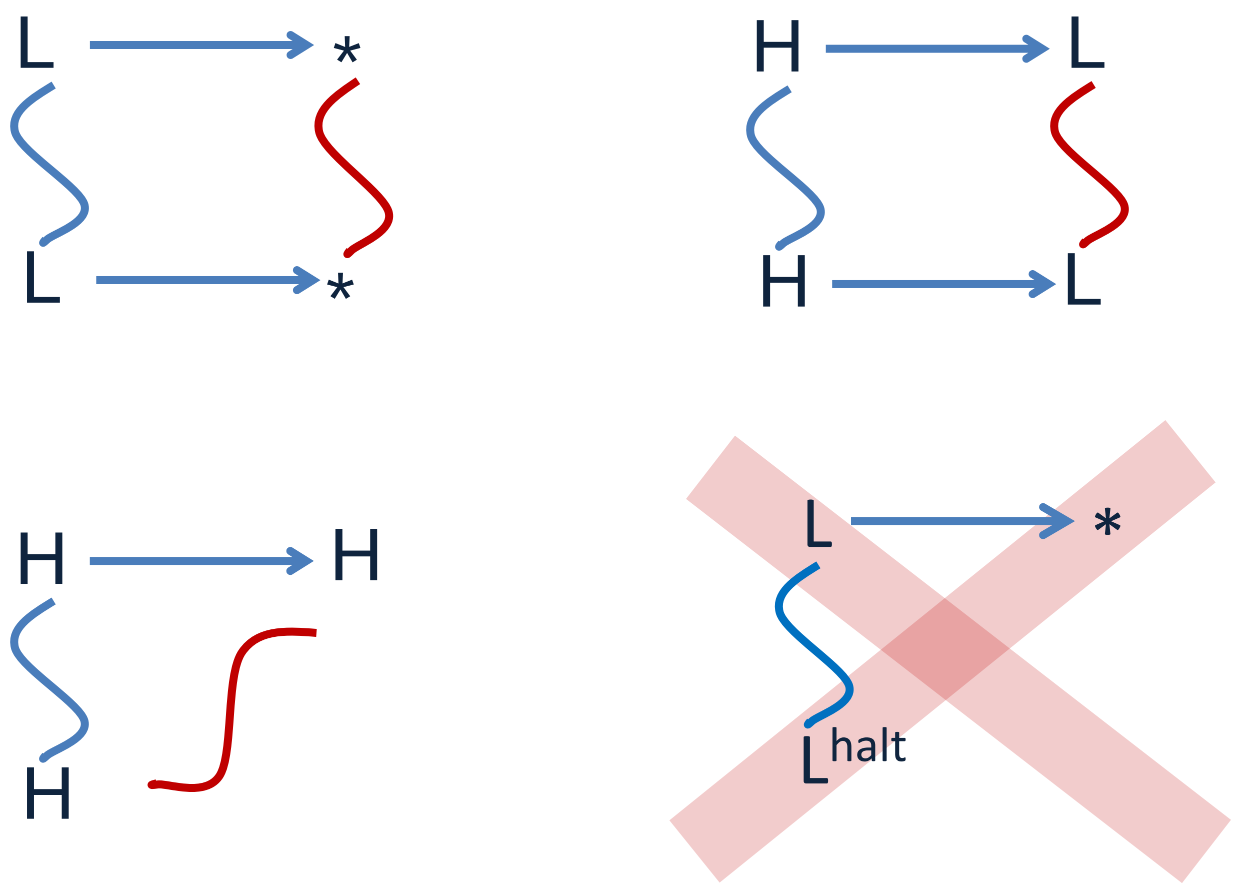


Even stronger noninterference



Single-step noninterference (SSNI)

easiest to test and suitable for proof ("unwinding conditions")



SSNI finds each bug in under 17ms

	EENI (with all improvements)	SSNI
Arith. mean MTTF	1526.75ms	2.01ms
Geom. mean MTTF	46.48ms	0.47ms
tests/s	2391	18407
discard rate	69%	9%

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discard rate	69%	9%

Tradeoff:

SSNI requires discovering stronger invariants

invariants of real SAFE machine are very complicated

Why shrink counterexamples?

memory	stack	next instruction
[0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[]	Push {0/15}@H
[0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[{0/15}@H]	Load
[0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[0@L]	Pop
[0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[]	Push -5@L
[0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[-5@L]	Push 17@L
[0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[17@L,-5@L]	Push 0@L
[0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[0@L,17@L,-5@L]	Store
[17@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[-5@L]	Push 1@L
[17@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[1@L,-5@L]	Store
[17@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[]	Push {21/3}@H
[17@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[{21/3}@H]	Push 2@L
[17@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[2@L,{21/3}@H]	Load
[17@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[0@L,{21/3}@H]	Pop
[17@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[{21/3}@H]	Push 1{/0}@H
[17@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[1{/0}@H,{21/3}@H]	Push 8@L
[17@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[8@L,1{/0}@H,{21/3}@H]	Store
[17@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,1{/0}@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[{21/3}@H]	Push {9/17}@H
[17@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,1{/0}@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[{9/17}@H,{21/3}@H]	Push {3/0}@H
[17@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,1{/0}@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[{3/0}@H,{9/17}@H,{21/3}@H]	Load
[17@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,1{/0}@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L]	[{0/17}@L,{9/17}@H,{21/3}@H]	Store
[{9/17}@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,1{/0}@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,{0/17}@L,0@L,0@L,0@L]	[{21/3}@H]	Push 3@L
[{9/17}@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,1{/0}@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,{0/17}@L,0@L,0@L,0@L]	[3@L,{21/3}@H]	Push 1@H
[{9/17}@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,1{/0}@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,{0/17}@L,0@L,0@L,0@L]	[1@H,3@L,{21/3}@H]	Load
[{9/17}@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,1{/0}@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,{0/17}@L,0@L,0@L,0@L]	[-5@L,3@L,{21/3}@H]	Pop
[{9/17}@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,1{/0}@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,{0/17}@L,0@L,0@L,0@L]	[3@L,{21/3}@H]	Push 1@L
[{9/17}@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,1{/0}@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,{0/17}@L,0@L,0@L,0@L]	[1@L,3@L,{21/3}@H]	Push 19@L
[{9/17}@L,-5@L,0@L,0@L,0@L,0@L,0@L,0@L,1{/0}@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,0@L,{0/17}@L,0@L,0@L,0@L]	[19@L,1@L,3@L,{21/3}@H]	Halt

Shrinking

- greedy search for smaller counterexample
- lots of different tricks/heuristics/black magic:
  - shrinking variations together
  - smart shrinking (optimizes order to gain speed)
  - double shrinking (take two steps in one)
- domain-specific knowledge crucial
- future: experimentally assess our shrinking

Potential extensions

- estimate expected error in our experiments
- evaluate against other testing techniques
  - we blow symbolic execution out of the water
  - still need to try exhaustive and narrowing based testing (SmallCheck, Lazy SmallCheck, EasyCheck)
- test other IFC mechanisms
  - high-level languages: Breeze and LIO
  - static type systems

Beyond noninterference

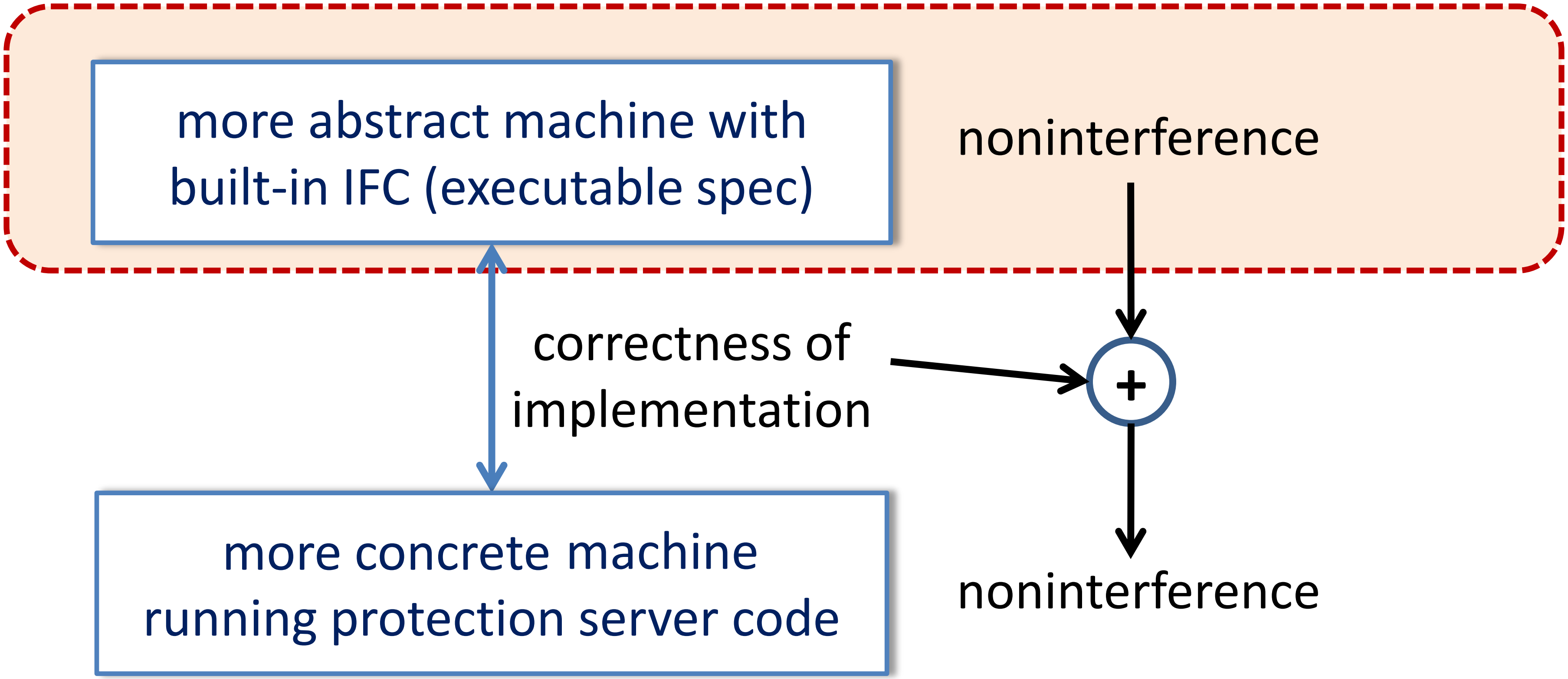
- testing other properties:
  - general relational ones (program logics)
  - some results on testing refinement / simulation
  - semantics preserving translations (exception handling mechanisms)
    - All Your IFCException Are Belong To Us talk on Monday at 8:45am at Oakland 2013

More potential future work on testing

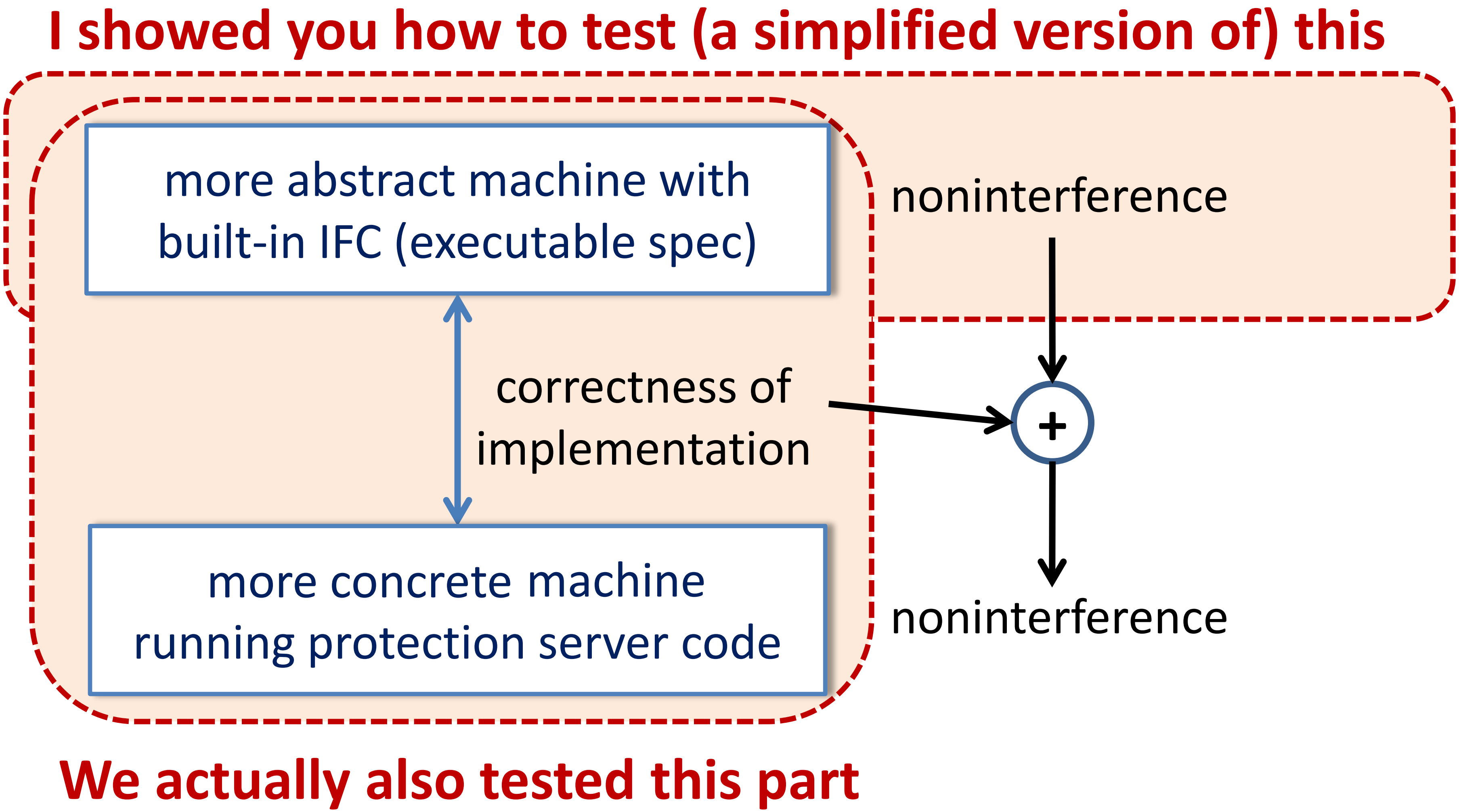
- how to make random testing as repeatable as unit testing?
  - how to save all bugs without turning code into spaghetti?
  - or how to add bugs automatically?
    - missing checks + taints are rather easy
- generic random testing framework for Coq
  - testing Coq very much behind wrt Isabelle
  - we don't need much beyond extraction to get started
- random testing: from art to science

Beyond testing

I showed you how to test (a simplified version of) this

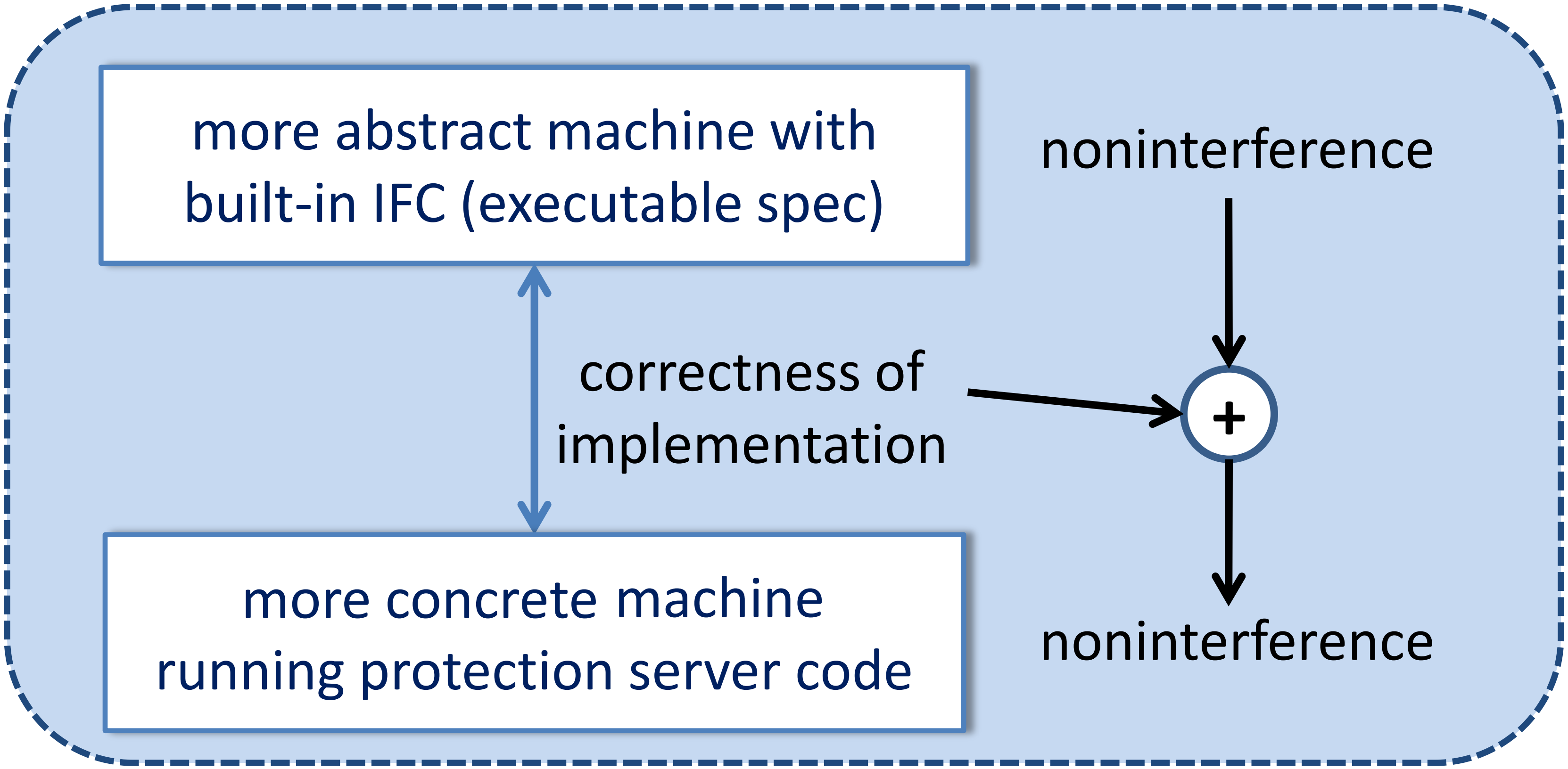


Beyond testing



Beyond testing

Testing is a great prelude to formal verification



We proved all this in Coq (for this 10 instr. machine; real machine 10x more complex though)

Conclusion

- property-based random testing
  - is a lot of fun
  - can inform and greatly speed up design process
  - can serve as 1st step towards formal verification
    - concentrate more energy on proving things that are correct or nearly correct; finding the right invariants
  - is not push-button
    - but some general tricks help a lot
    - incorporating domain knowledge crucial: about the system and the property