Reasoning About a Machine with Local Capabilities

Provably Safe Stack and Return Pointer Management

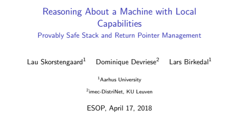
Lau Skorstengaard[1] Dominique Devriese[2] Lars Birkedal[1]

[1]Aarhus University

[2]imec-DistriNet, KU Leuven

ESOP, April 17, 2018

2018-04-13



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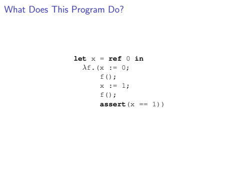
What Does This Program Do?

```
let x = ref 0 in
  λf.(x := 0;
      f();
      x := 1;
      f();
      assert(x == 1))
```



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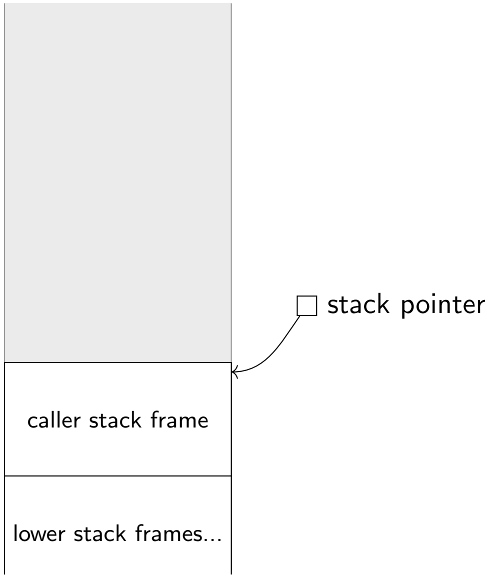
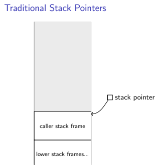
Informally, what does this program do?It allocates a reference to 0 and saves a closure to x. The closure takes a callback, assigns 0 to x, calls the callback, assigns 1 to x, calls the callback another time and finally asserts x to be 1.As a programmer that is how I would think. But what happens if I compile this closure to assembly and let some untrusted piece of code interact with it?My reasoning depends on the assumption that when I call f, then if f returns it returns to a certain point. The low-level machine needs to enforce this if I want to be able to do have this closure interact with arbitrary machine code.

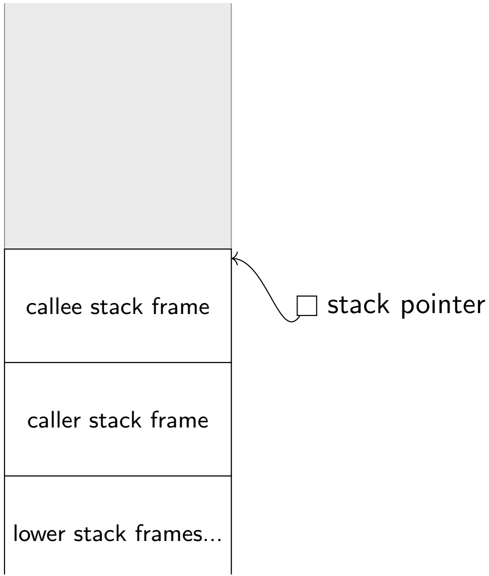
Traditional Stack Pointers

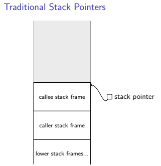




Let's first consider what happens with the stack during a call on a traditional low-level machine and what can go wrong.We need something to enforce security properties on a low-level machine.

Traditional Stack Pointers





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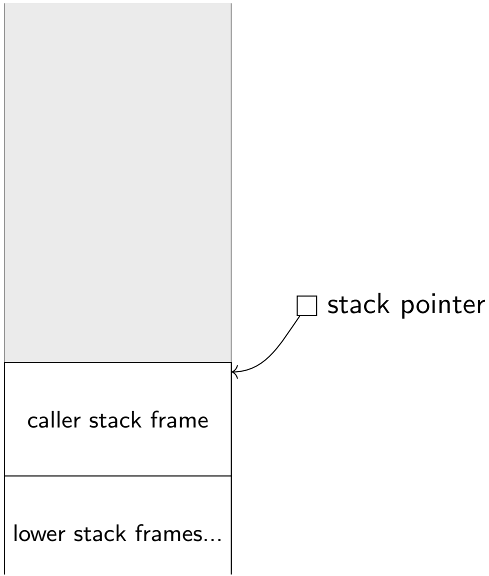

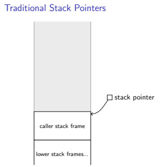

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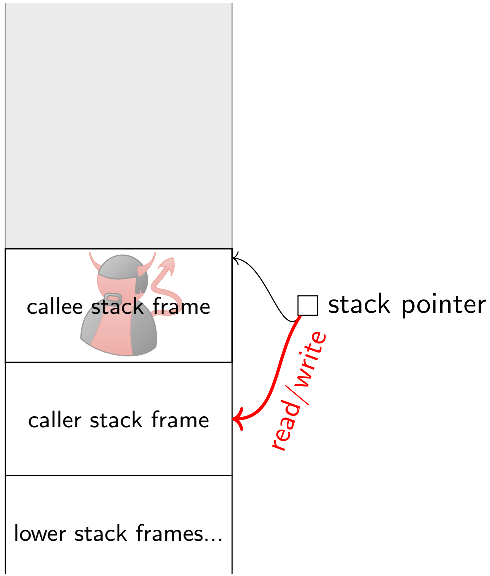
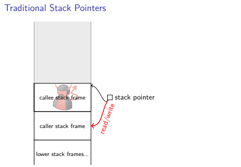
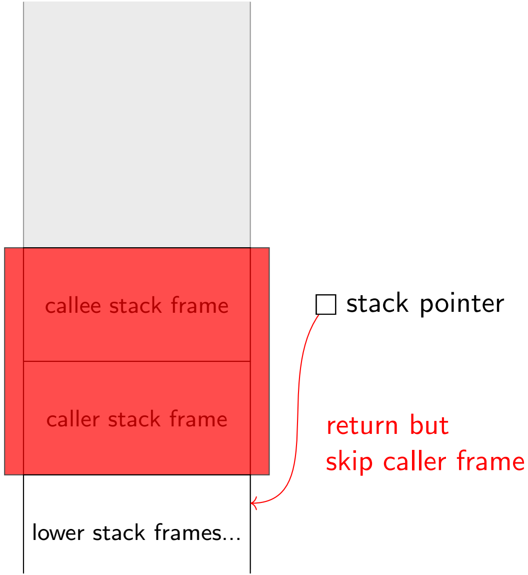
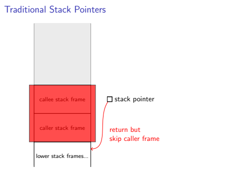



Traditional Stack Pointers
callee stack frame
caller stack frame
lower stack frames...
stack pointer
read/write

Let’s first consider what happens with the stack during a call on a traditional low-level machine and what can go wrong.We need something to enforce security properties on a low-level machine.

Traditional Stack Pointers





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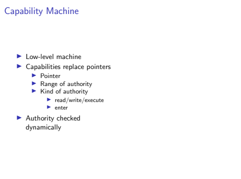
Capability Machine

- Low-level machine
- Capabilities replace pointers
  - Pointer
  - Range of authority
  - Kind of authority
    - read/write/execute
    - enter
- Authority checked dynamically



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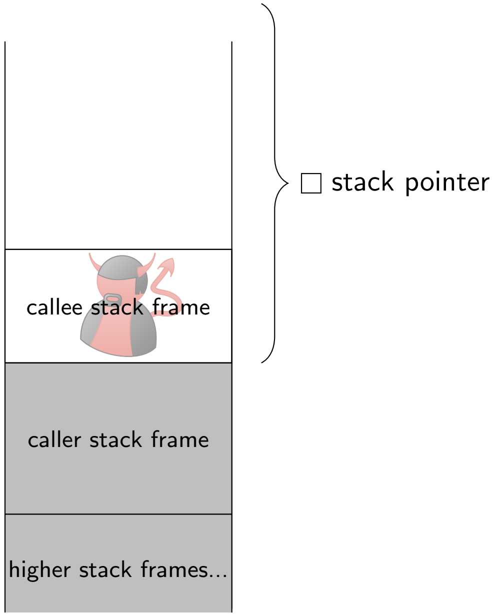
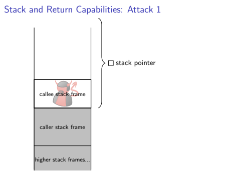
Has instructions as you would expect, load, store, jmp, etc.Has instructions for manipulating capabilities.This particular setup gives a very fine-grained memory control.

Stack and Return Capabilities: Attack 1

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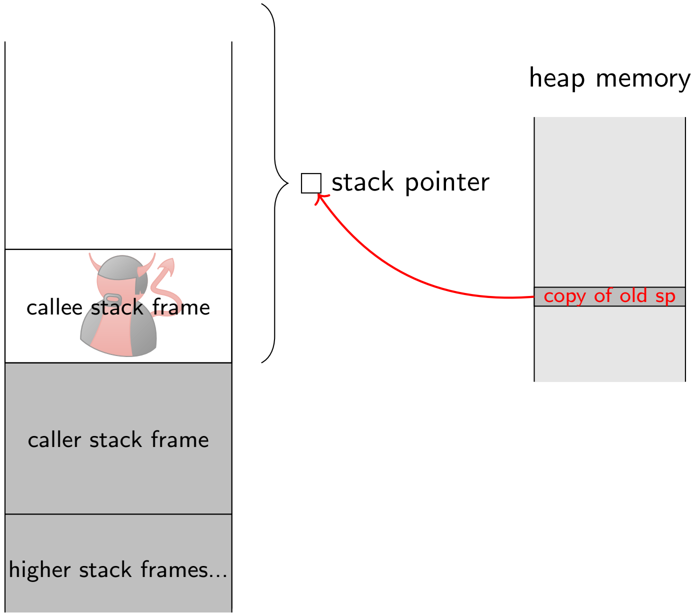

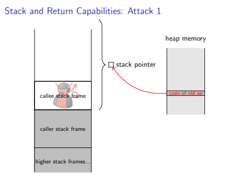

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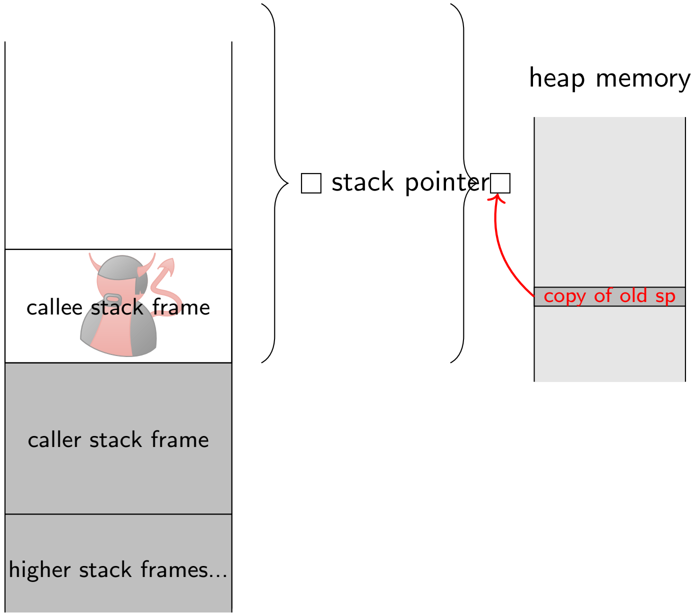

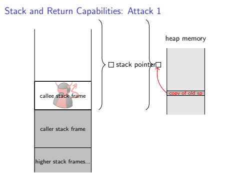

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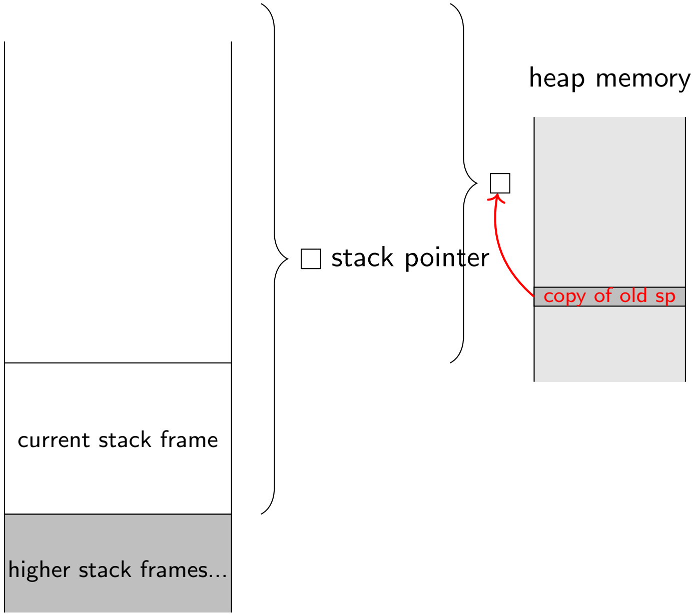

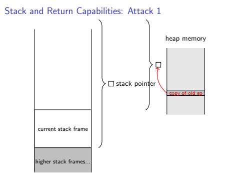

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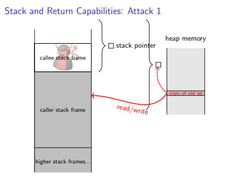

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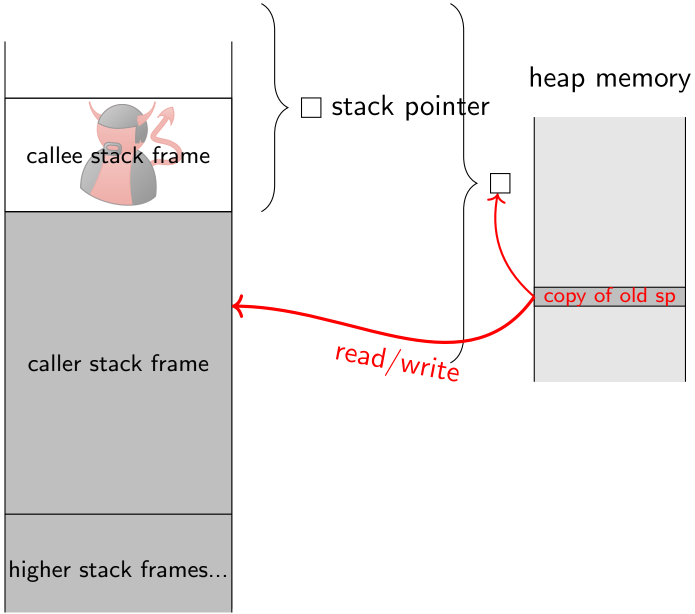

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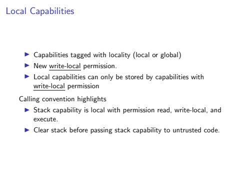
Local Capabilities

- Capabilities tagged with locality (local or global)
- New <u>write-local</u> permission.
- Local capabilities can only be stored by capabilities with <u>write-local</u> permission

Calling convention highlights

- Stack capability is local with permission read, write-local, and execute.
- Clear stack before passing stack capability to untrusted code.



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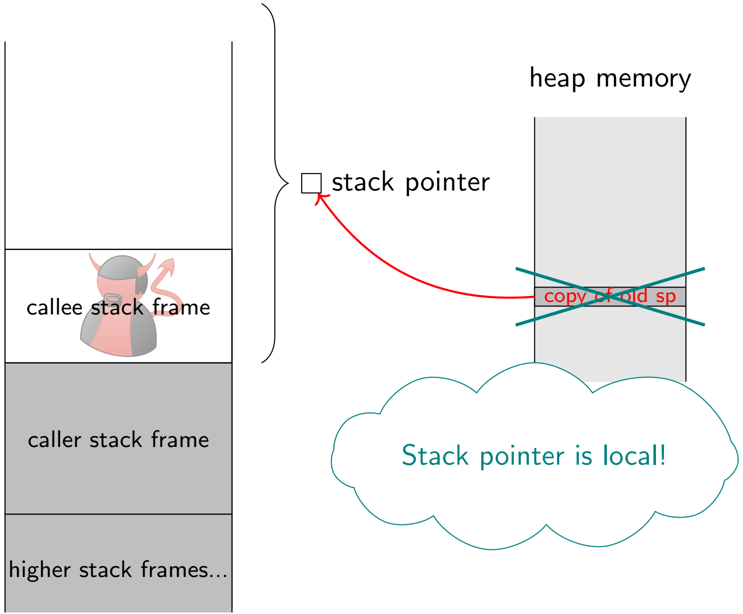
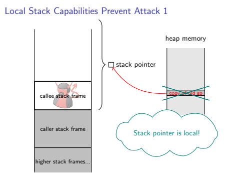
We call non-local capabilities global

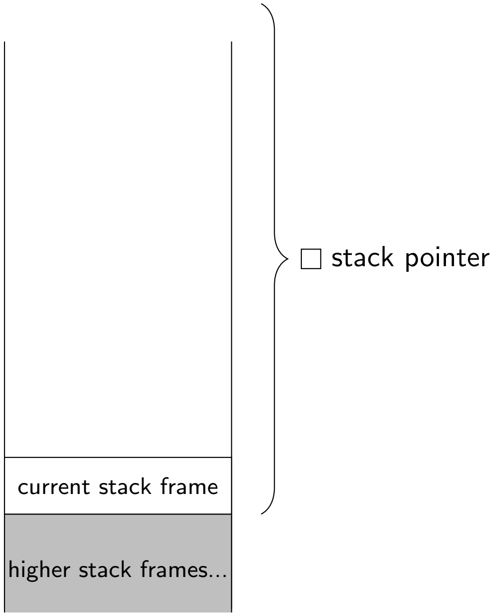
Local Stack Capabilities Prevent Attack 1

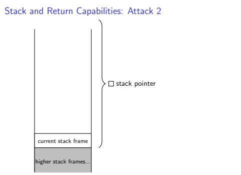


Stack pointer is local!



Stack and Return Capabilities: Attack 2




Stack and Return Capabilities: Attack 2

□ stack pointer

current stack frame

higher stack frames...

The stack was the only place to store the local capability, so the adversary hid it there.

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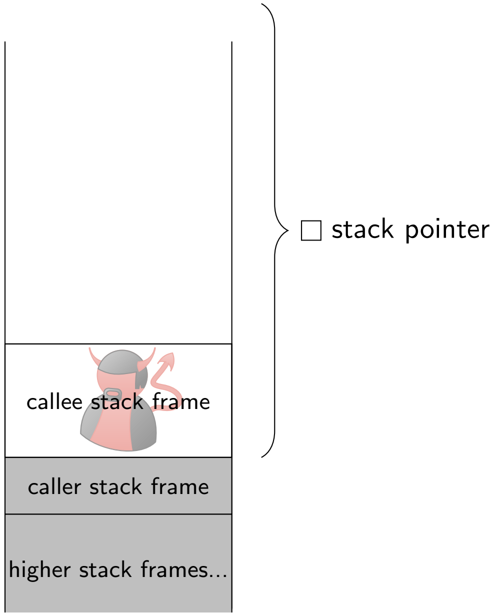

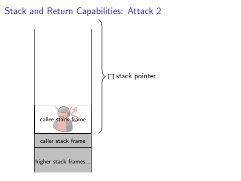
Stack and Return Capabilities: Attack 2

□ stack pointer
callee stack frame
caller stack frame
higher stack frames...

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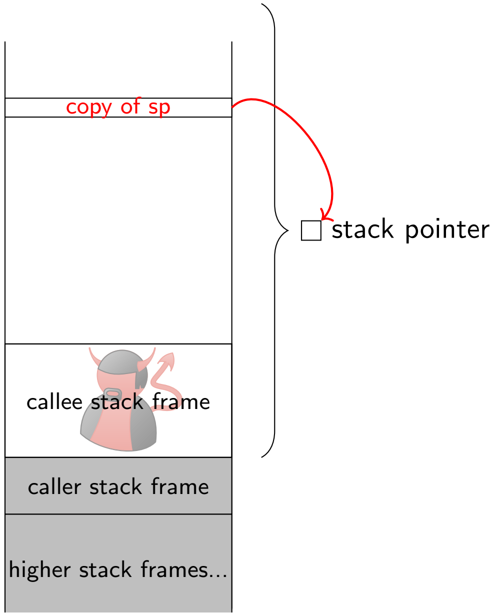

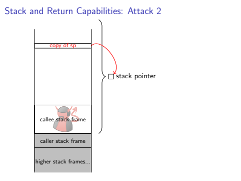

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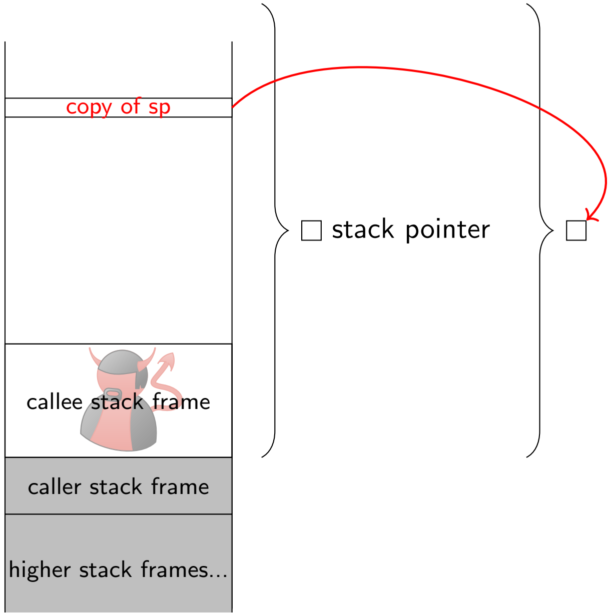

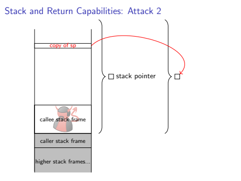

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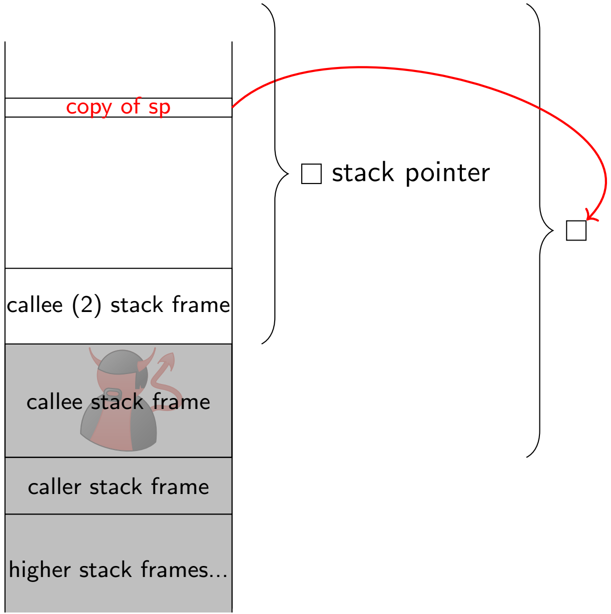


copy of sp

□ stack pointer

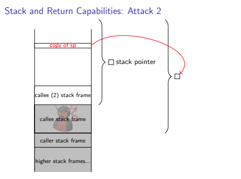
□

callee (2) stack frame

callee stack frame

caller stack frame

higher stack frames...



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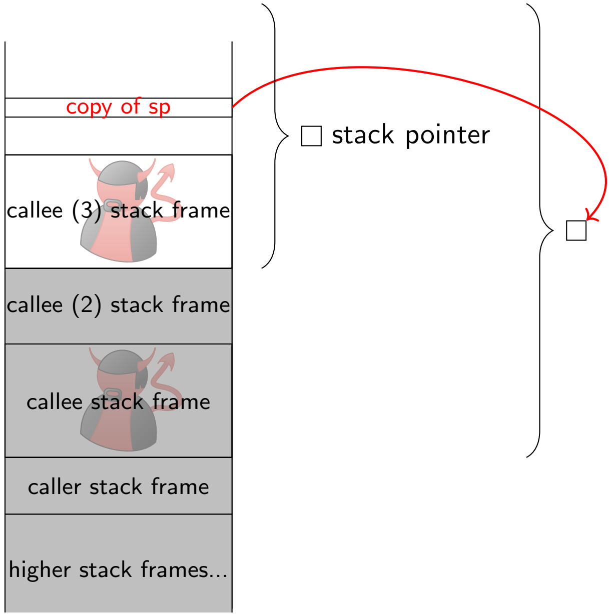

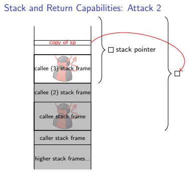

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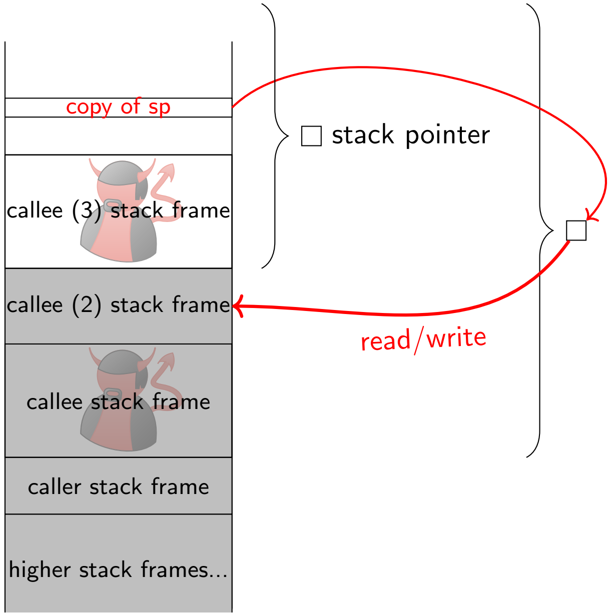

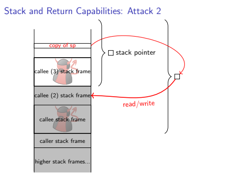

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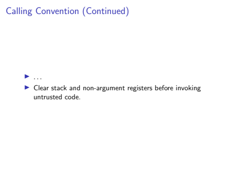
Calling Convention (Continued)

- . . .
- Clear stack and non-argument registers before invoking untrusted code.



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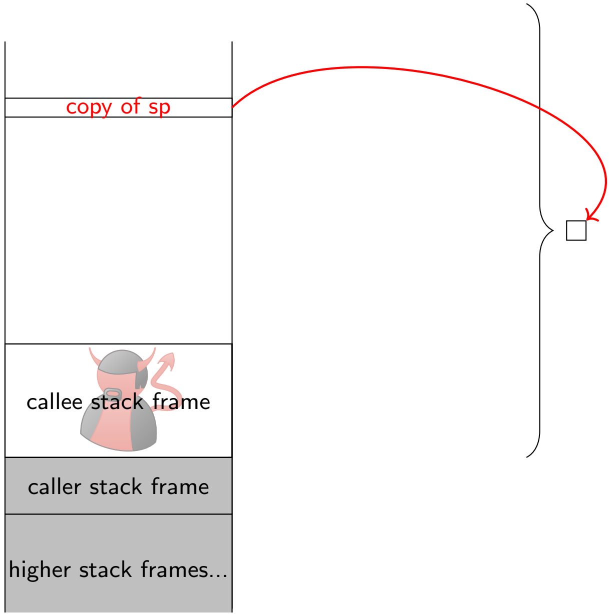
Stack Clearing Prevents Attack 2



Reasoning About a Machine with Local Capabilities

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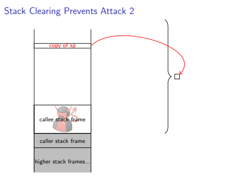

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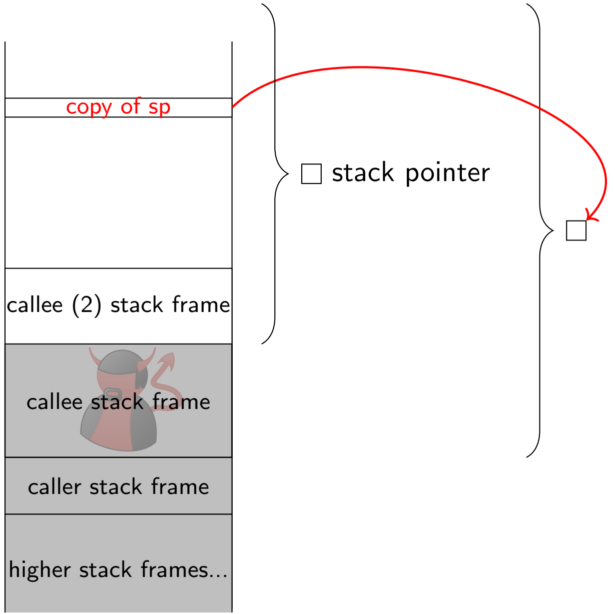

copy of sp

□ stack pointer

□

callee (2) stack frame

callee stack frame

caller stack frame

higher stack frames...

2018-04-13

Reasoning About a Machine with Local Capabilities

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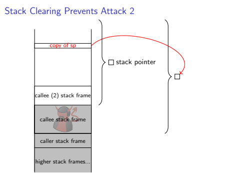

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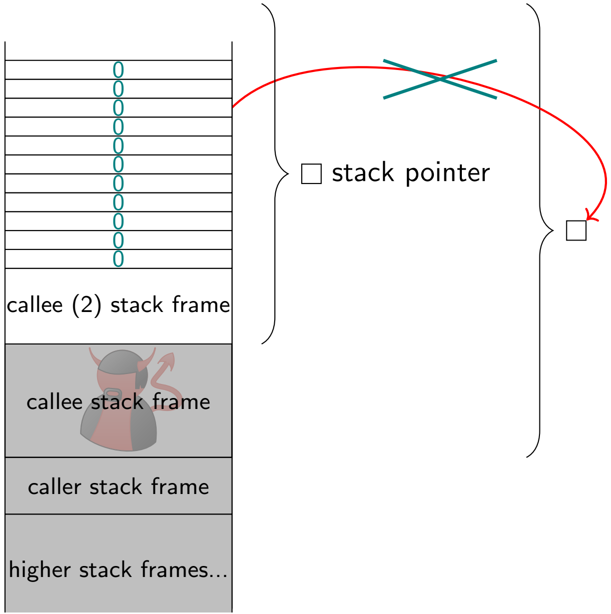

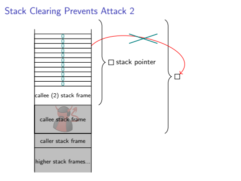

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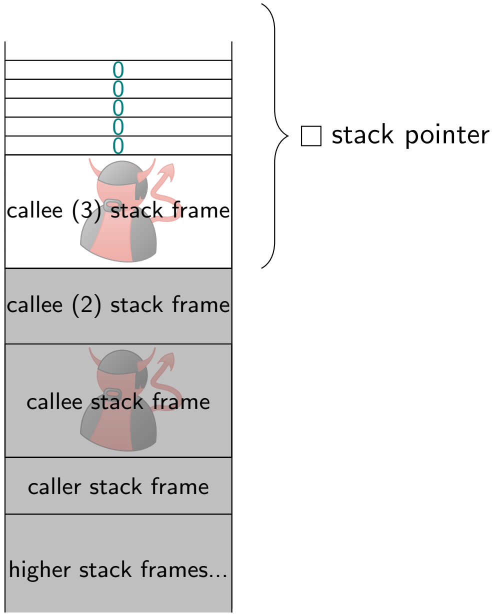

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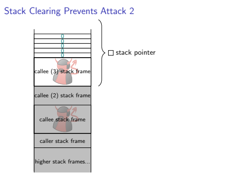
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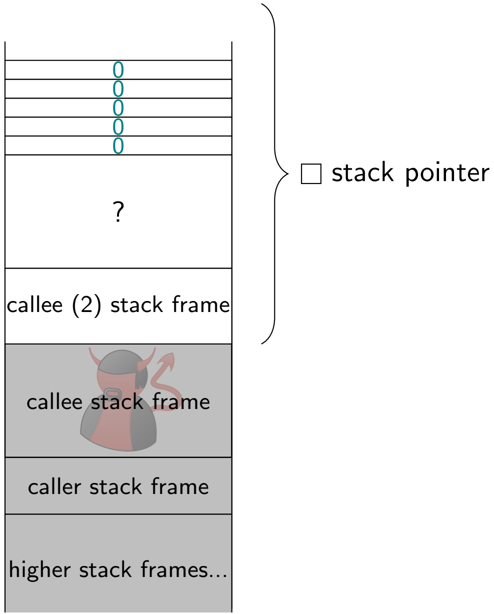


0
0
0
0
0

?

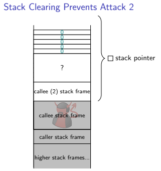
callee (2) stack frame

callee stack frame

caller stack frame

higher stack frames...

□ stack pointer



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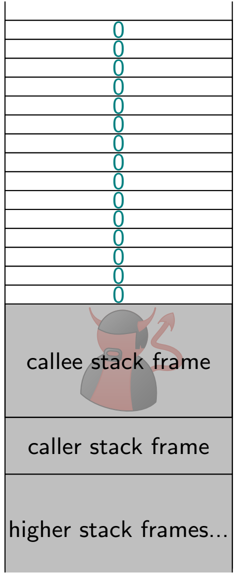

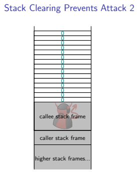

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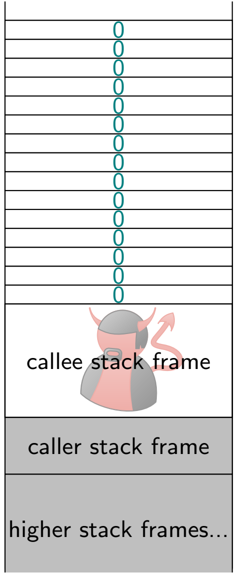

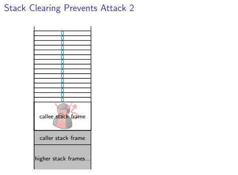

(Full) Calling Convention

- Initially:
  - Stack capabilitiy local capability with read, write-local, and execute authority.
  - No global write-local capabilities on the machine.
- Prior to returning to untrusted code:
  - Clear the stack.
  - Clear non-return registers.
- Prior to calls to untrusted code:
  - Push activation record to the stack and create enter-capability.
  - Restrict the stack pointer to the unused part and clear that part.
  - Clear non-argument registers.
- Only invoke global call-backs.
- When invoked by untrusted code
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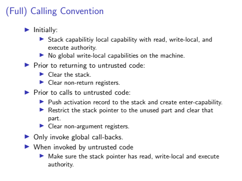


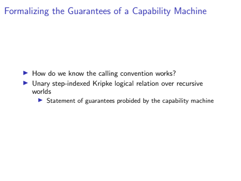
(Full) Calling Convention

- Initially:
  - Stack capabilitiy local capability with read, write-local, and execute authority.
  - No global write-local capabilities on the machine.
- Prior to returning to untrusted code:
  - Clear the stack.
  - Clear non-return registers.
- Prior to calls to untrusted code:
  - Push activation record to the stack and create enter-capability.
  - Restrict the stack pointer to the unused part and clear that part.
  - Clear non-argument registers.
- Only invoke global call-backs.
- When invoked by untrusted code
  - Make sure the stack pointer has read, write-local and execute authority.

We need to do a few more things, but this is the rest (just to illustrate that it is fairly simple).Every point is motivated by some attack.

Formalizing the Guarantees of a Capability Machine

- How do we know the calling convention works?
- Unary step-indexed Kripke logical relation over recursive worlds
    - Statement of guarantees probided by the capability machine


Formalizing the Guarantees of a Capability Machine

- How do we know the calling convention works?
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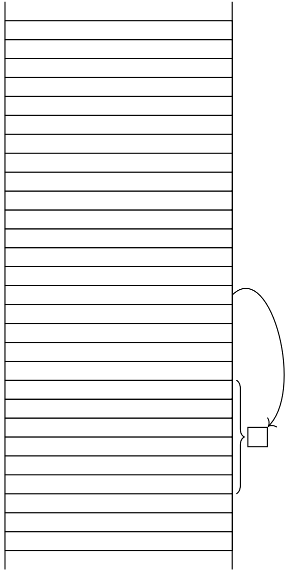
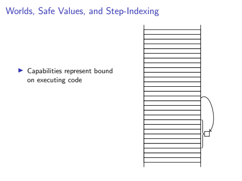
How can we be sure calling convention works. Specifically, if a program interacts with intrusted code using the CC, can we formally show the correctness of the program if it relies on well-bracketedness or local-state encapsulation.Need formal statement of the guarantees provided by the capability machine including the specific guarantees for local capabilities.We state this formal statement in terms of a unary step-indexed Kripke logical relation over recursive worldsCalling convention main application, but it is very general - can be used to reason about other programs.In the following: give some intuition for different parts of LRcorrectness here could be assert not violatedmention better than previous. Define the guarantees

Worlds, Safe Values, and Step-Indexing

- Capabilities represent bound on executing code





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- World, W
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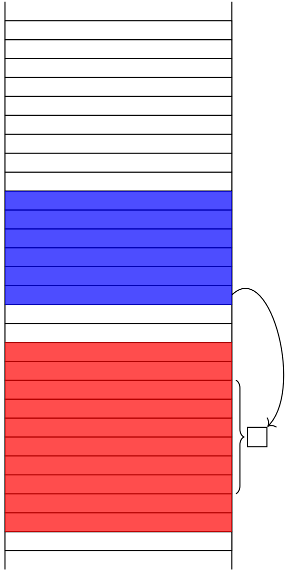

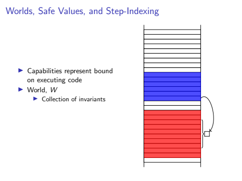

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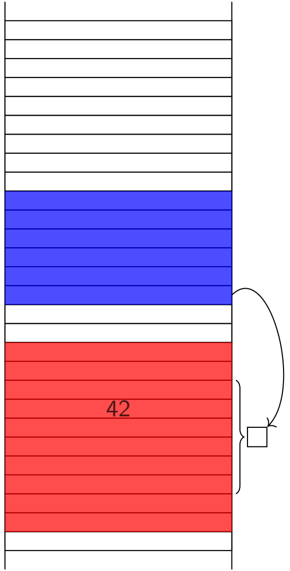

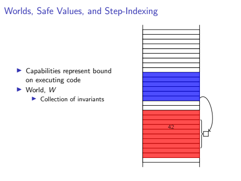
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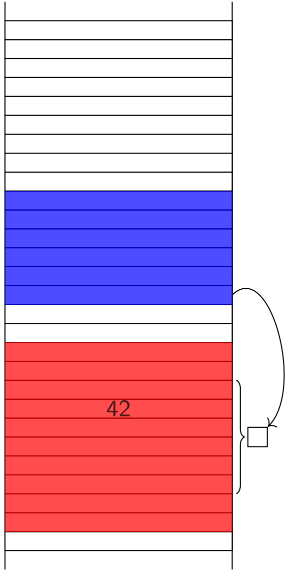

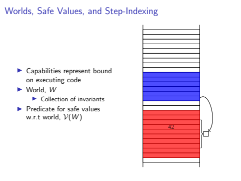
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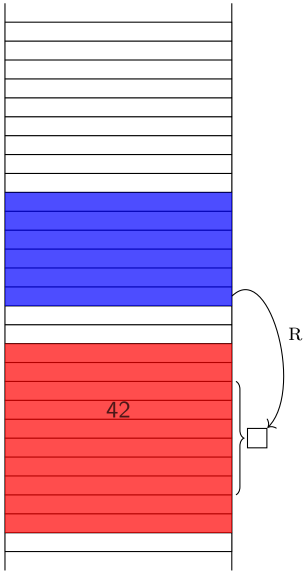

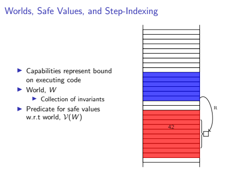
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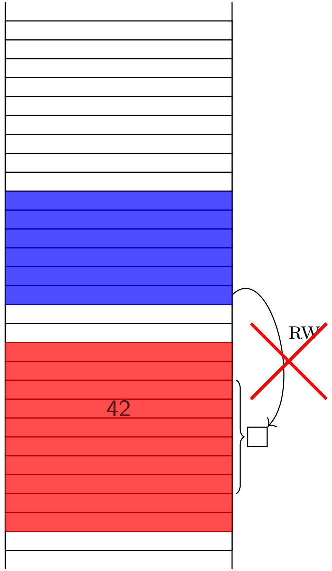

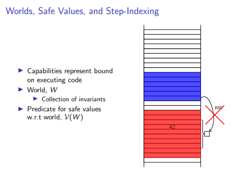

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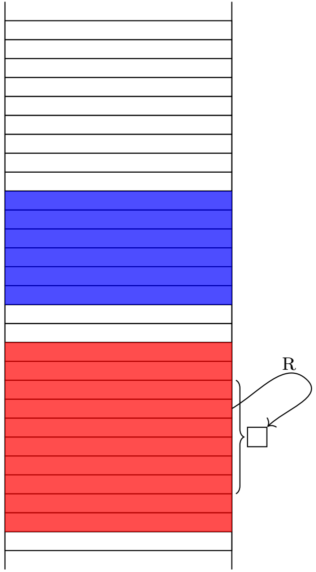

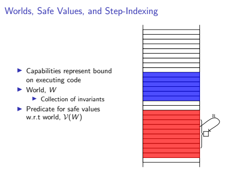
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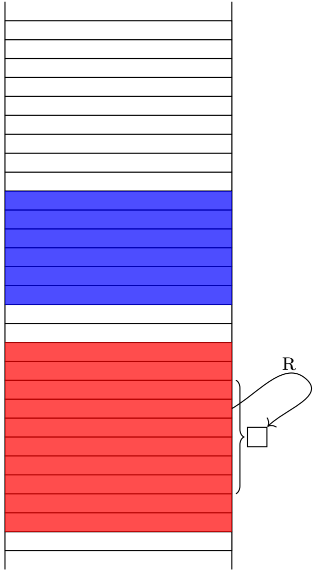
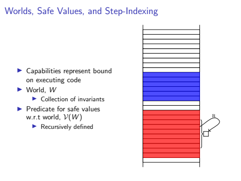
  - Recursively defined

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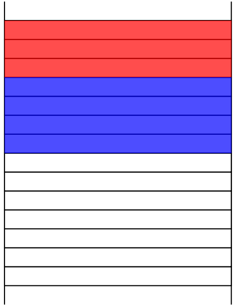
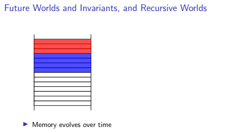
Future Worlds and Invariants, and Recursive Worlds



- Memory evolves over time



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Memory changes over time, for instance new memory may be allocated.Allow worlds to evolve. New invariants can be added to handle freshly allocated memory.Safety of words monotone w.r.t. worlds (which makes it into a Kripke Logical relation).

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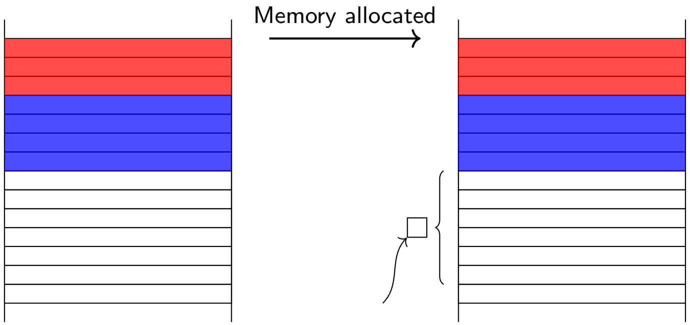

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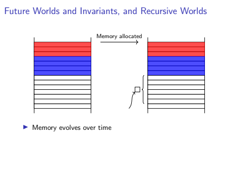

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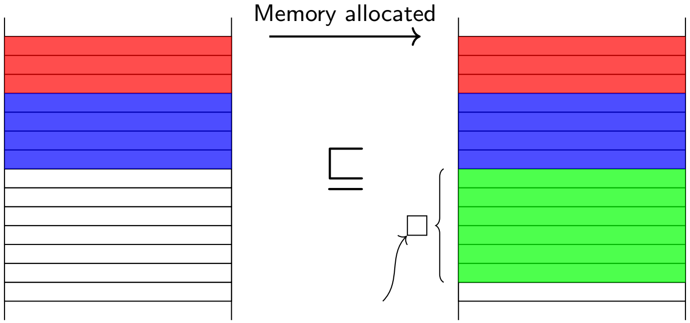
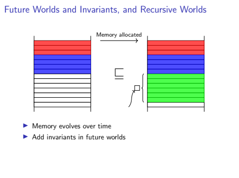


- Memory evolves over time
- Add invariants in future worlds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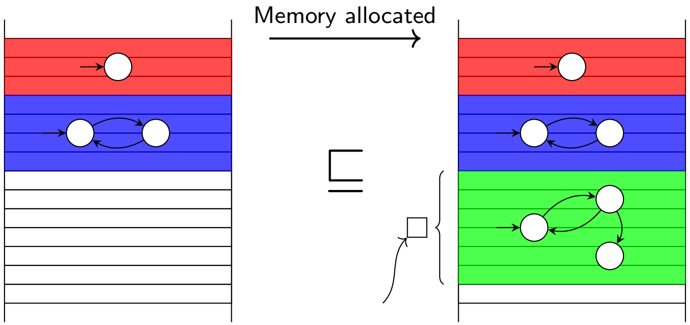

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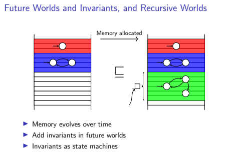
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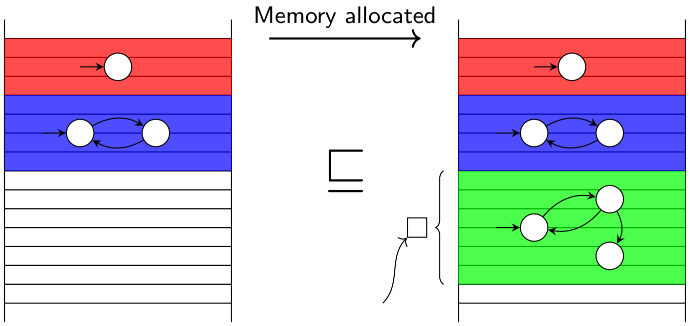
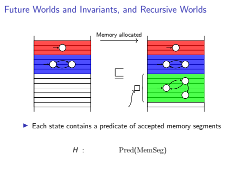


- Each state contains a predicate of accepted memory segments

$$H : \qquad \mathrm{Pred}(\mathrm{MemSeg})$$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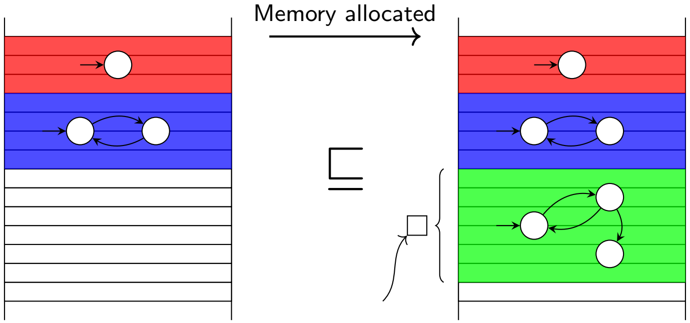

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- World indexed

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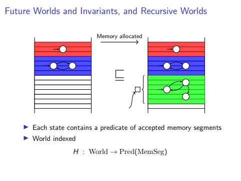
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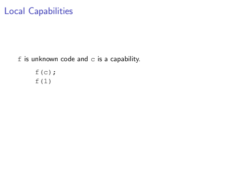
Local Capabilities

f is unknown code and c is a capability.

```
f(c);
f(1)
```



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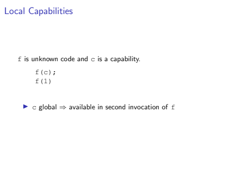
- `c` global ⇒ available in second invocation of `f`



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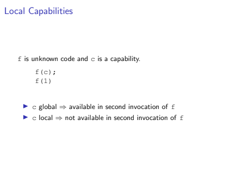
- c global ⇒ available in second invocation of f
- c local ⇒ not available in second invocation of f



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- c global ⇒ available in second invocation of f
- c local ⇒ not available in second invocation of f

when c global, second invocation in a world where c is safewhen c local, second invocation in a world where c is not (necessarily) safec essentially revoked, so the invariants it relies on need not hold.Two future world relations, one for all capabilities and one for non-local capabilitiesIf c global, then second invocation must happen in public future world, so c valid.If c local, then second invocation may happen in a private future world.How does local/global capabilities affect all this.If we hand a global capability to untrusted code, then it may be stored in memory, so we will only be able to reinvoke that code if we can guarantee that those values are still valid. Formally, the worlds contain the invariants that the global capability depend on and reinvocation is only possible in future worlds where these invariants are respected.Local capabilities on the other provides a means to revoke capabilities. If we invoke untrusted code and give them a local capability, then they have no way to store it aside from the register file (and the stack), so when they return we can be sure that the local capability

Local Capabilities

f is unknown code and c is a capability.

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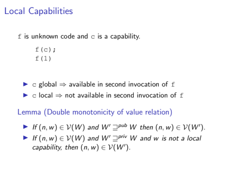
Lemma (Double monotonicity of value relation)

- *If* $(n, w) \in \mathcal{V}(W)$ *and* $W' \sqsupseteq^{pub} W$ *then* $(n, w) \in \mathcal{V}(W')$.
- *If* $(n, w) \in \mathcal{V}(W)$ *and* $W' \sqsupseteq^{priv} W$ *and* w *is not a local capability, then* $(n, w) \in \mathcal{V}(W')$.



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Fundamental Theorem of Logical Relations

- General statement about the guarantees provided by the capability machine.
- Intuitively: any program is safe as long as it only has access to safe values.

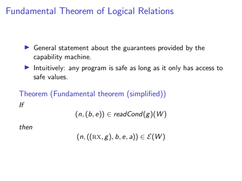
Theorem (Fundamental theorem (simplified))

If

$$(n, (b, e)) \in \mathit{readCond}(g)(W)$$

then

$$(n, ((\mathrm{RX}, g), b, e, a)) \in \mathcal{E}(W)$$



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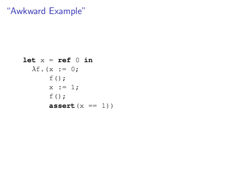
readCond is the assumption that every thing in the interval [a,e] is safe to read.$\mathcal{E}$ is safe to execute relation. That is, it will respect all the memory invariants.That is take an arbitrary capability. If it only has access to safe capabilities then it will preserve the invariants of the world.Remeber, dynamic checks = failing is concidered secure

“Awkward Example”

```
let x = ref 0 in
  λf.(x := 0;
      f();
      x := 1;
      f();
      assert(x == 1))
```



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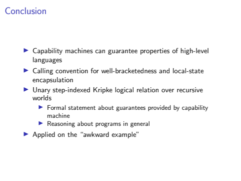
example known from the litteratureeven just in ML difficult as f can be the closure.the assert can fail if the calls are not well-bracketed!the local state is difficult to handle as the closure and the contex needs to be able to update the invariant for x in different ways. (closure can switch between 0 and 1 as it pleases, but context can transition only from 0 to 1.)relies heavily on well-bracketednesswe have made a faithfull translation and proved correctness (i.e., the assertion never fails).more semantic statement of guarantees allows us to do this.

Conclusion

- Capability machines can guarantee properties of high-level languages
- Calling convention for well-bracketedness and local-state encapsulation
- Unary step-indexed Kripke logical relation over recursive worlds
  - Formal statement about guarantees provided by capability machine
  - Reasoning about programs in general
- Applied on the “awkward example”



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Thank you!

Reasoning About a Machine with Local Capabilities

2018-04-13

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