StkTokens: Enforcing Well-Bracketed Control Flow and Stack Encapsulation Using Linear Capabilities

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[1]Aarhus University

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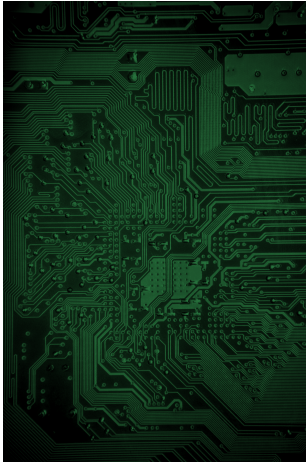
POPL, January 16, 2019

Abstractions all the way down



Abstractions all the way down

```
main:
  .cfi_startproc
# BB#0:
  pushq %rbp
.Ltmp0:
  .cfi\_def\_cfa\_offset 16
.Ltmp1:
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  movq  %rsp, %rbp
.Ltmp2:
  .cfi\_def\_cfa\_register %rbp
  subq  $16, %rsp
  movabsq $.L.str, %rdi
  movl  $0, -4(%rbp)
  movb  $0, %al
  callq printf
  xorl  %ecx, %ecx
  movl  %eax, -8(%rbp)
  movl  %ecx, %eax
  addq  $16, %rsp
  popq  %rbp
  retq
.Lfunc\_end0:
  .size main, .Lfunc\_end0-main
  .cfi\_endproc
```

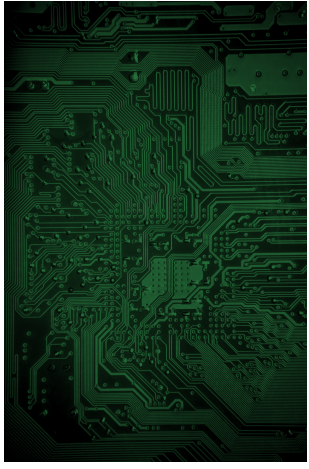

Abstractions all the way down

```c
#include <stdio.h>
int main()
{
  int t = 5;
  printf("Hello, World!");

  return 0;
}
```

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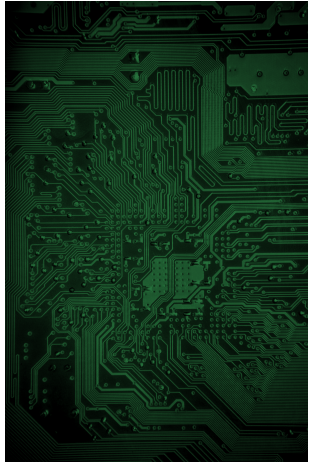

Abstractions all the way down

compilation

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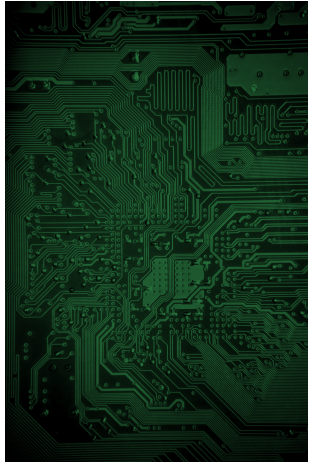

Abstractions all the way down

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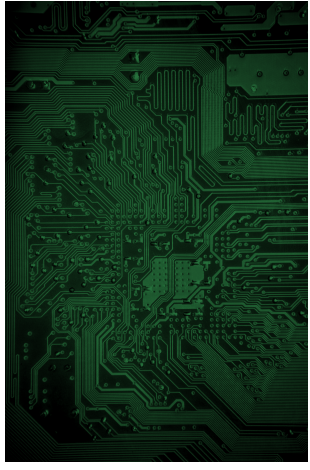

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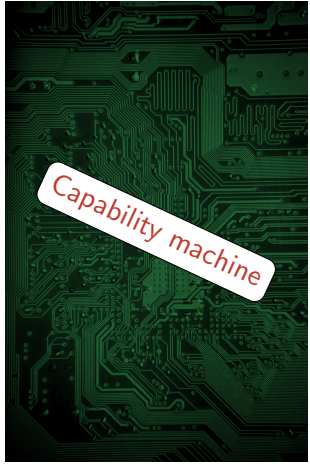

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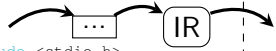


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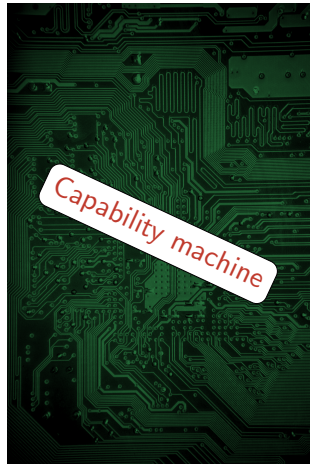
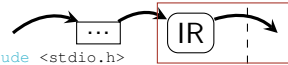


Abstractions all the way down

secure compilation

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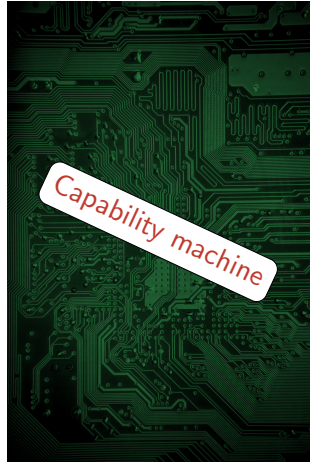

Well-bracketed control flow and local state encapsulation

```
void a()
{
    ...
    return;
}

void b()
{
    int x = 5;
    a();
    ...
    a();
    return;
}
```

Well-bracketed control flow and local state encapsulation

```
void a()
{
    ...
    return;
}
```

Function `a` cannot access variable `x`

```
void b()
{
    int x = 5;
    a();
    ...
    a();
    return;
}
```

Local-state encapsulation (LSE)

Well-bracketed control flow and local state encapsulation

```
void a()
{
    ...
    return;
}

void b()
{
    int x = 5;
    a();
    ...
→   a();
    return;
}
```

Well-bracketed control flow (WBCF)

Well-bracketed control flow and local state encapsulation

```
→ void a()
  {
      ...
      return;
  }

  void b()
  {
      int x = 5;
      a();
      ...
      a();
      return;
  }
```

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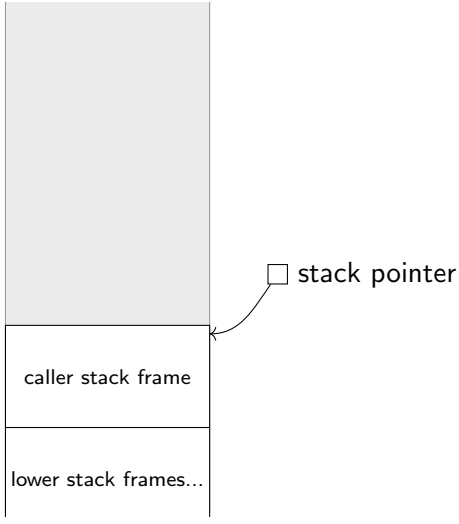
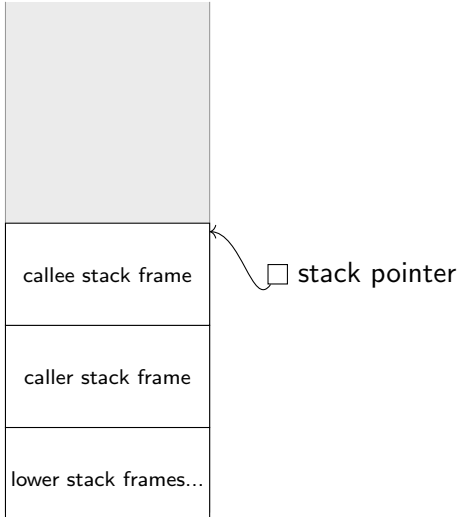
Well-bracketed control flow (WBCF)

Traditional stack pointers



Traditional stack pointers



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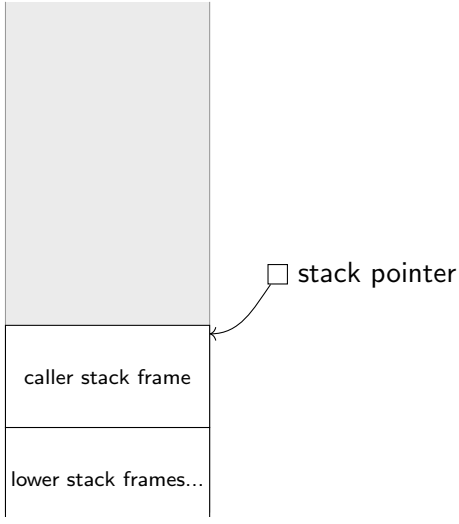

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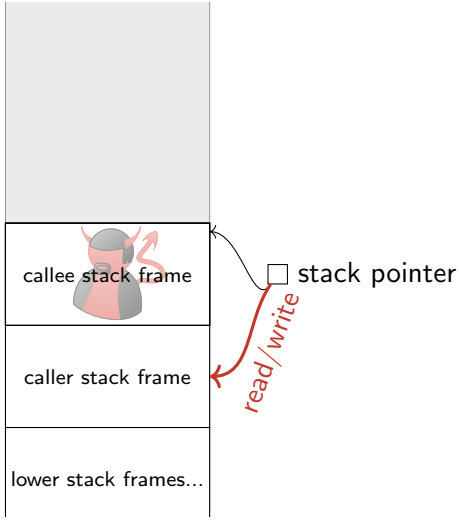

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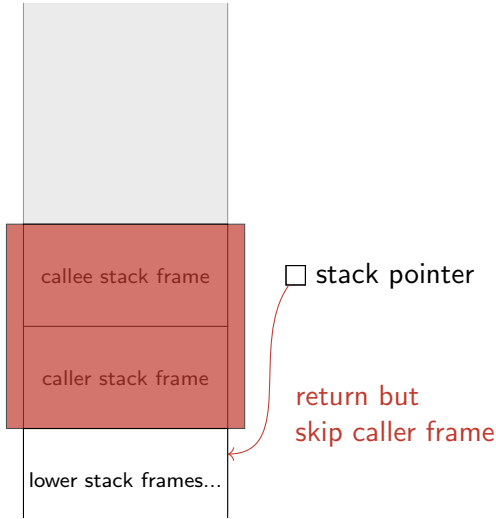
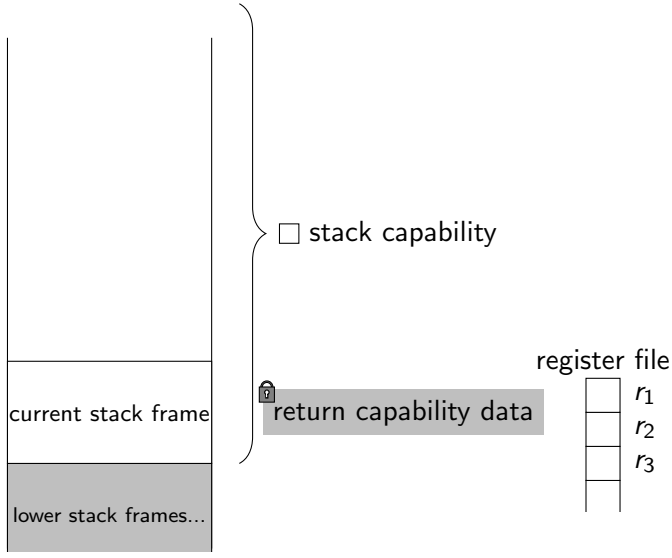


Naive stack and return capabilities



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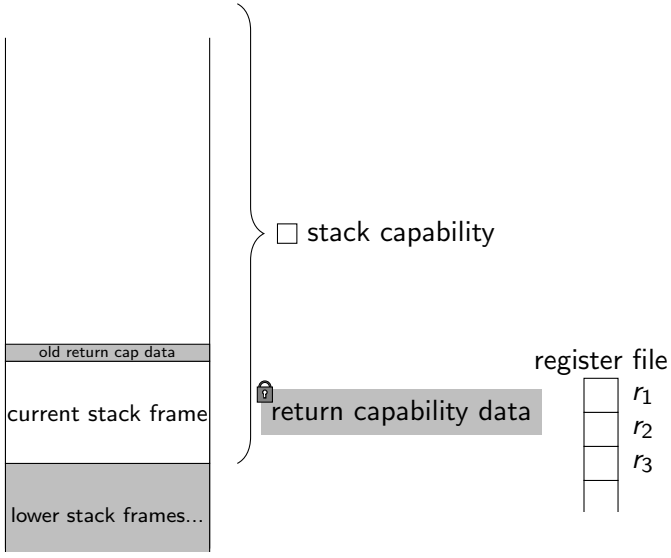

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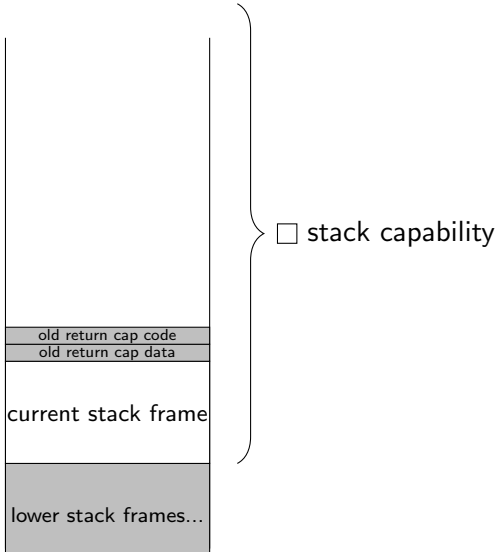

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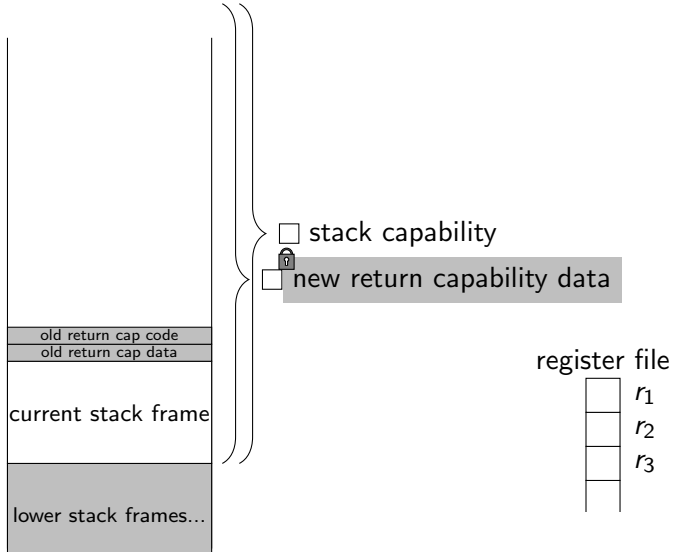

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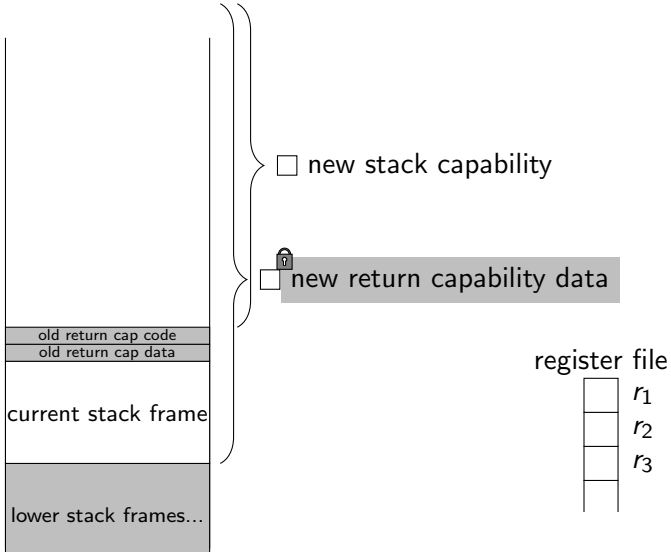

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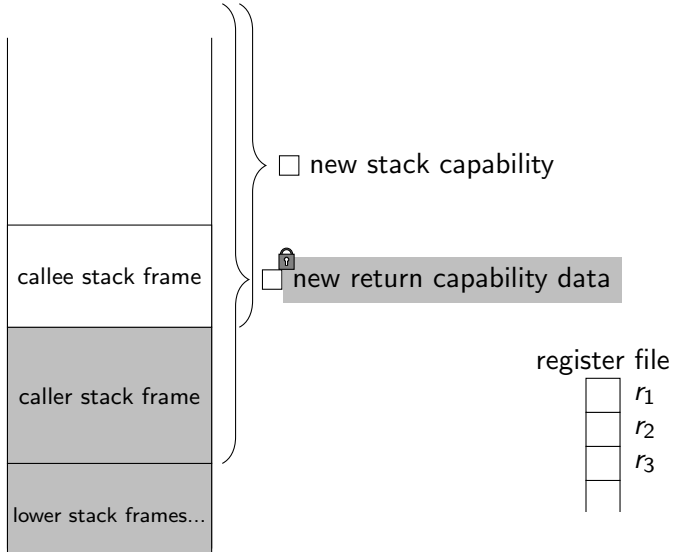
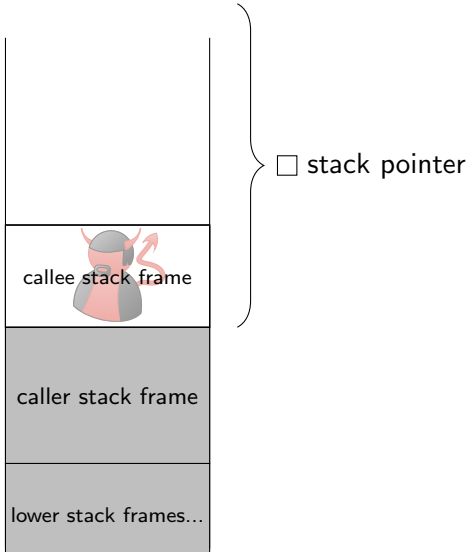


Attack on naive stack and return capabilities



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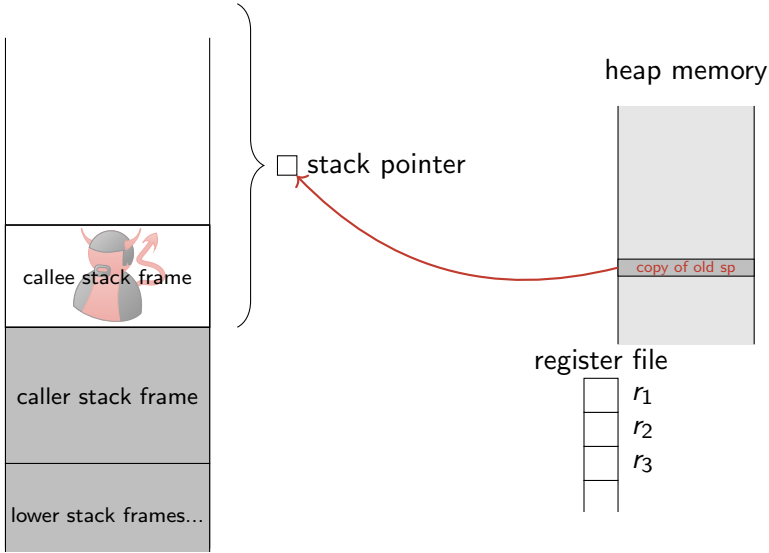

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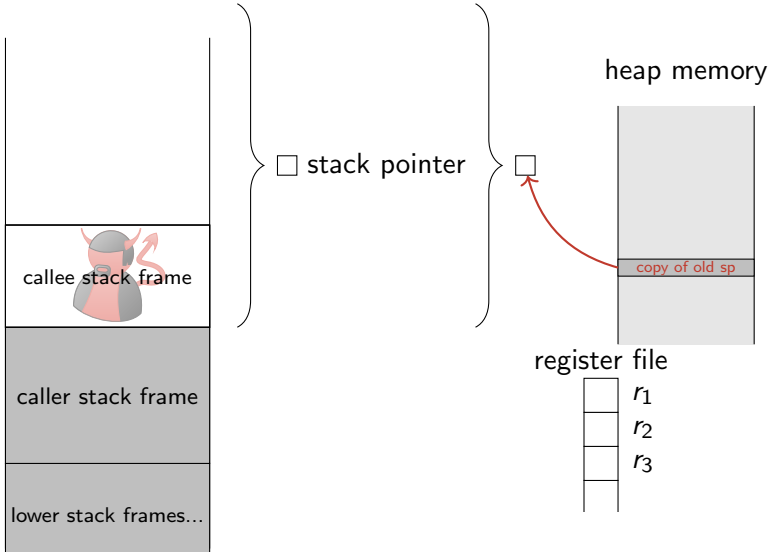

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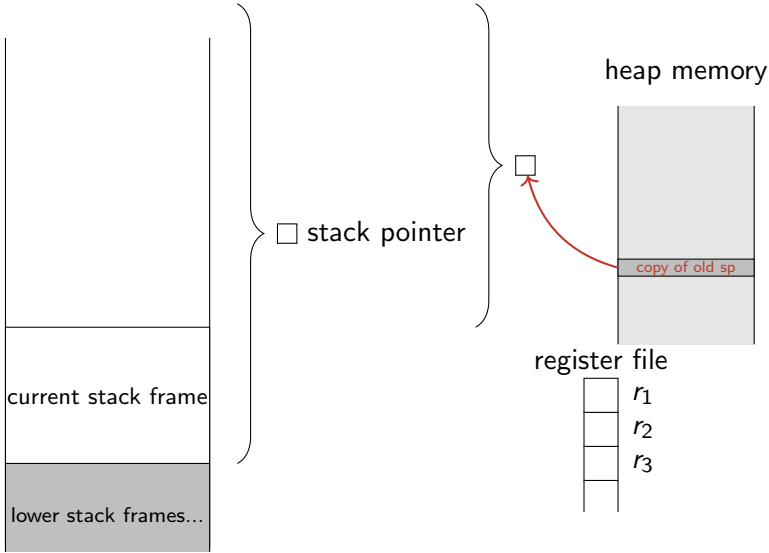

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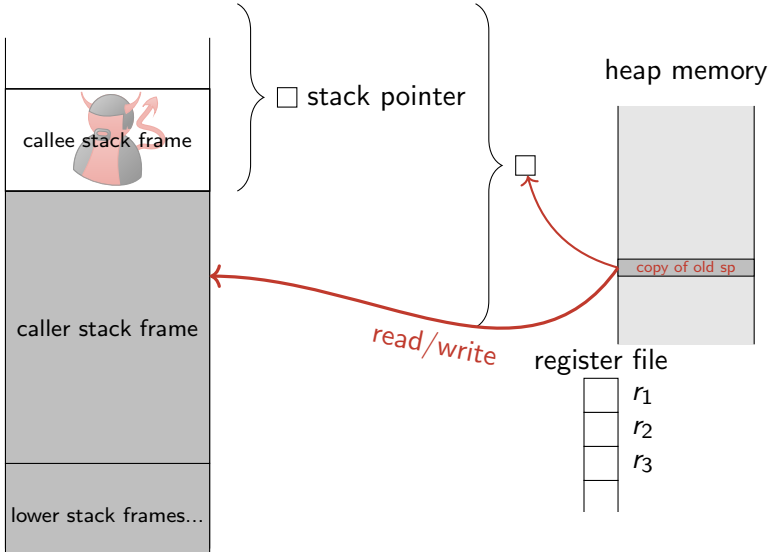
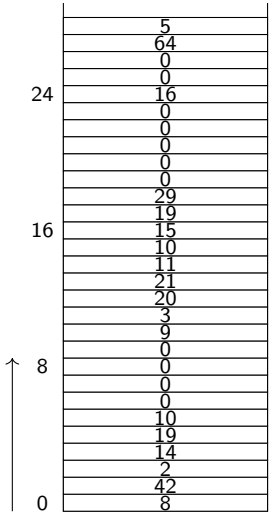


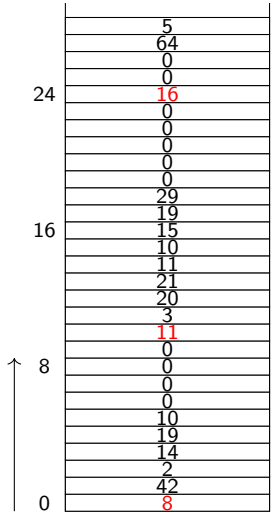
Linear capabilities



Register File

8
0
24
16
2

Linear capabilities



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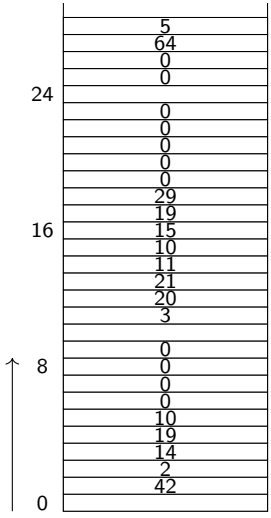
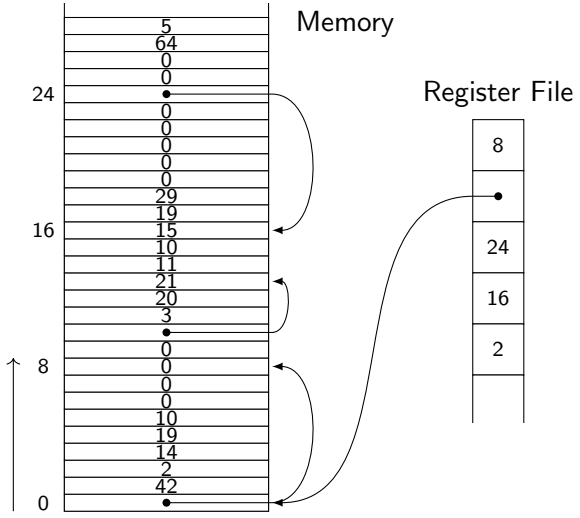


Register File

Replace pointers with capabilities

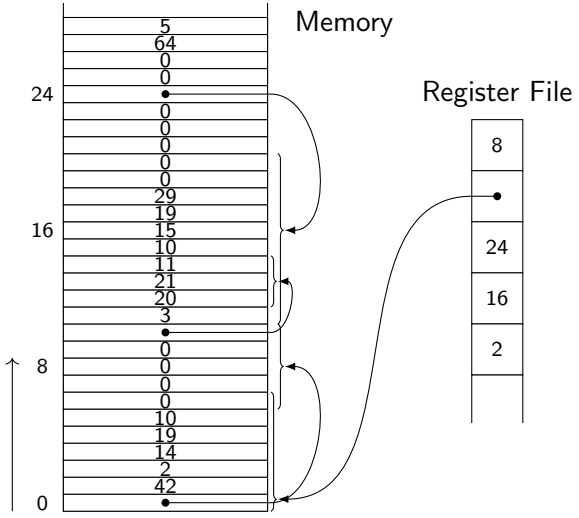
Linear capabilities



Replace pointers with capabilities

- Pointer

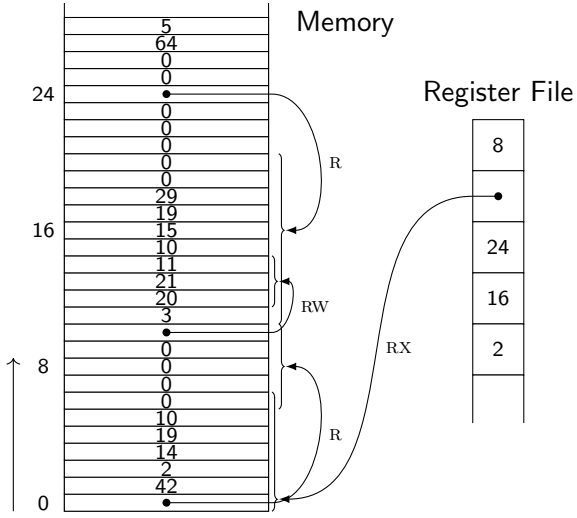
Linear capabilities



Replace pointers with capabilities

- Pointer
- Range of authority

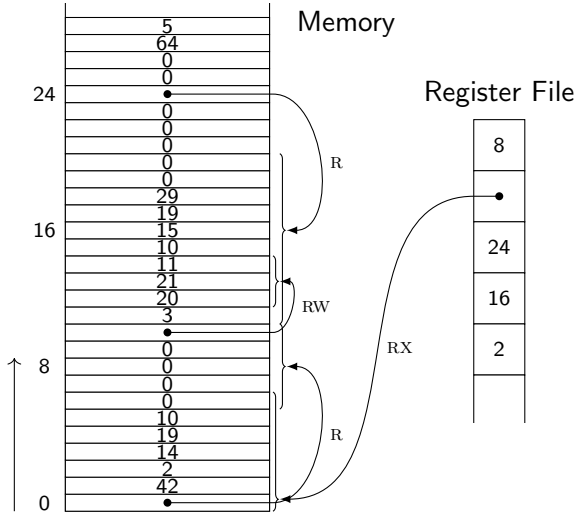
Linear capabilities



Replace pointers with capabilities

- Pointer
- Range of authority
- Permission

Linear capabilities

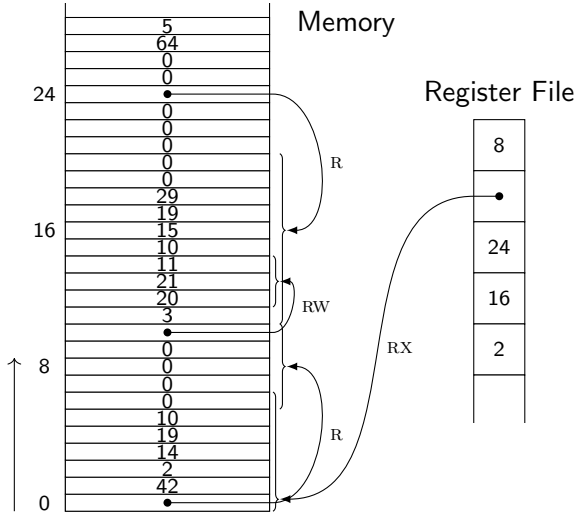


Replace pointers with capabilities

- Pointer
- Range of authority
- Permission

Dynamically enforced

Linear capabilities



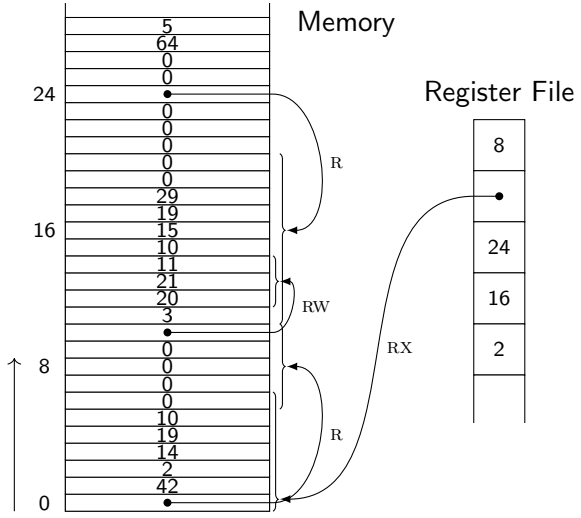
Replace pointers with capabilities

- Pointer
- Range of authority
- Permission

Dynamically enforced

- Cap. aware instructions

Linear capabilities



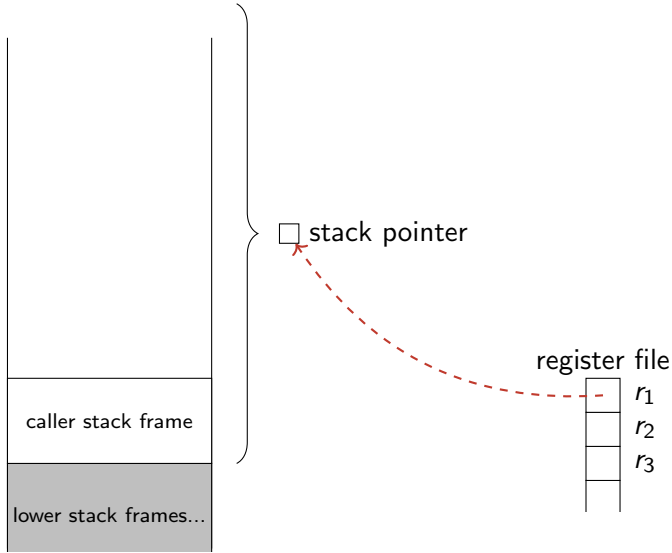
Replace pointers with capabilities

- Pointer
- Range of authority
- Permission

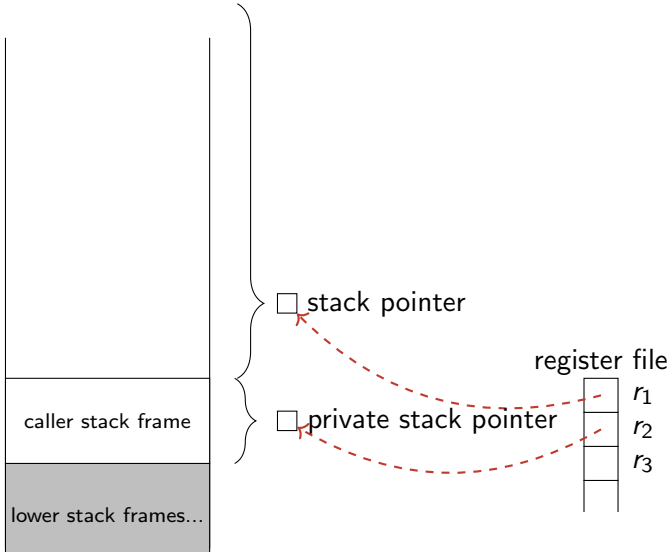
Dynamically enforced

- Cap. aware instructions
- Tagged memory

StkTokens prevents the attack



StkTokens prevents the attack



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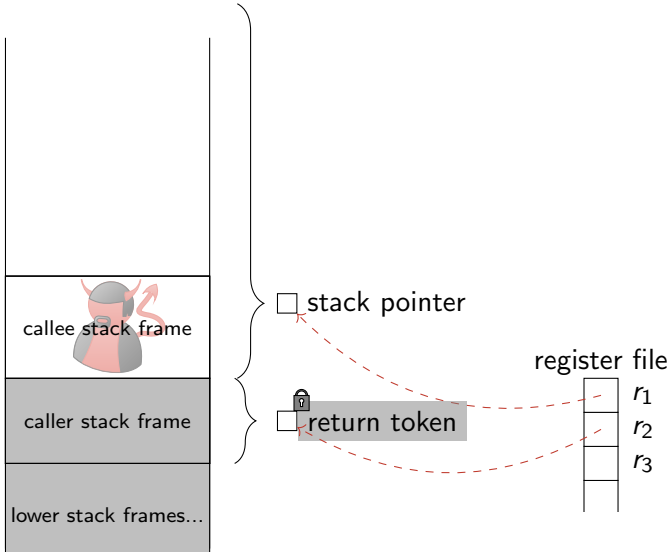

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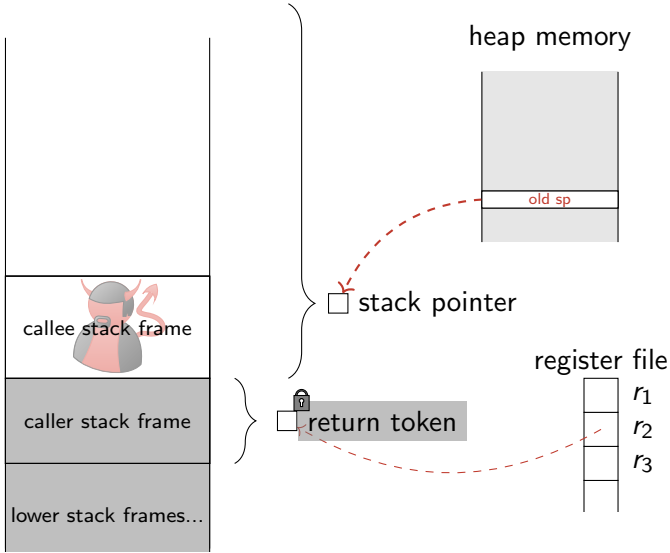

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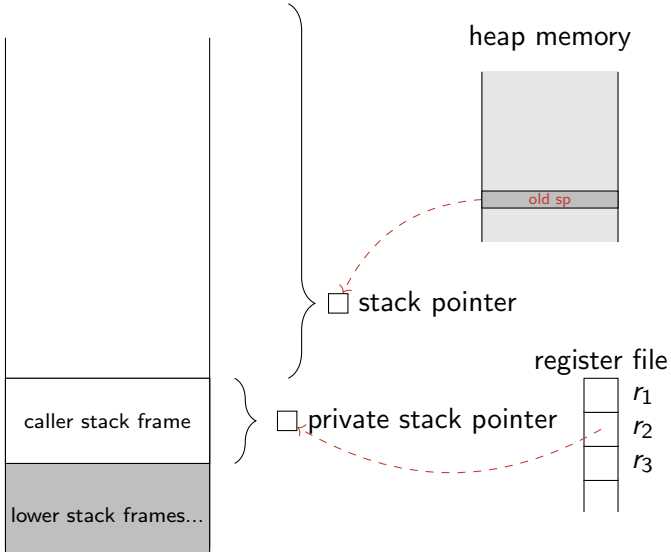

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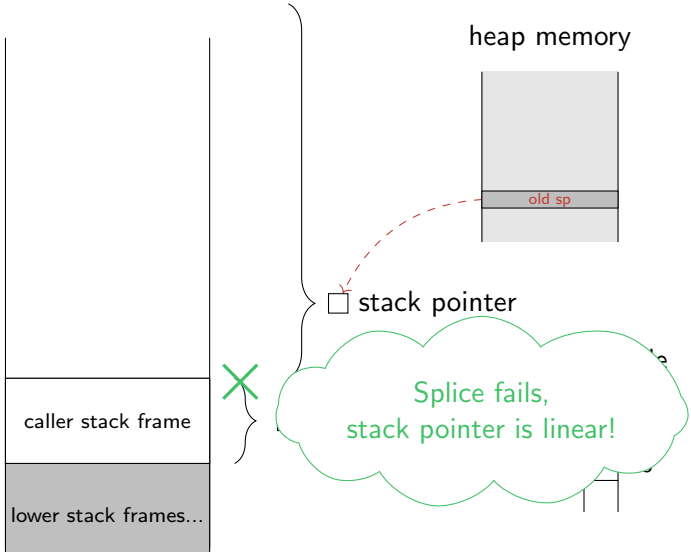

Fully-abstract overlay semantics

```
move  rtmp1 42
store rstk rtmp1
cca   rstk -1
geta  rtmp1 rstk
cca   rretc 5
move  rtmp1 pc
cca   rtmp1 -20
```

```
load  rtmp1 rtmp1
cca   rtmp1 -21
cseal rretd rtmp1
move  rretc pc
xjmp  r1 r2
cseal rretc rtmp1
move  rtmp1 0
```

Linear Capability Machine

Fully-abstract overlay semantics

```
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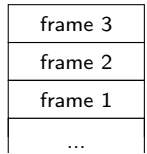
Builtin call stack



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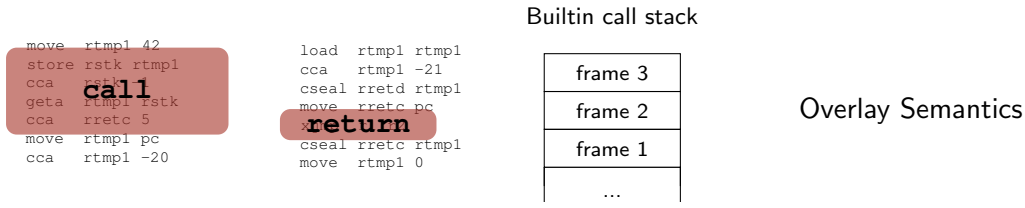
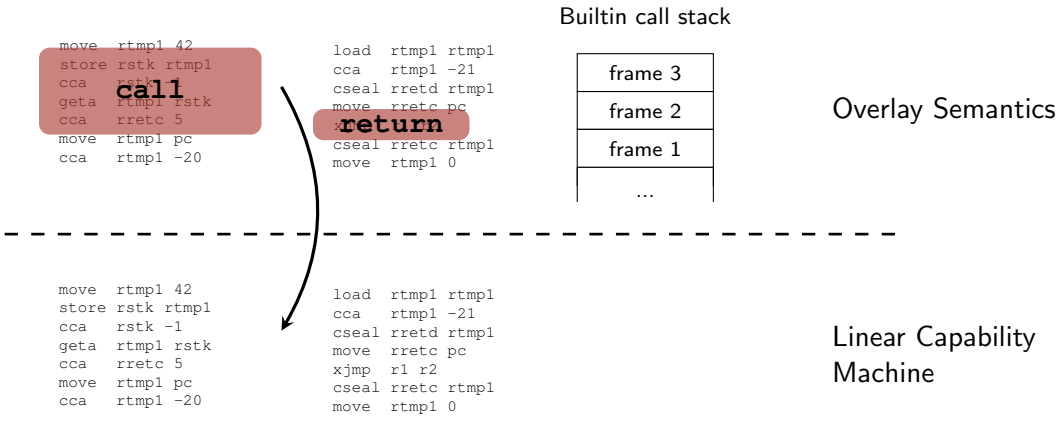
Linear Capability Machine

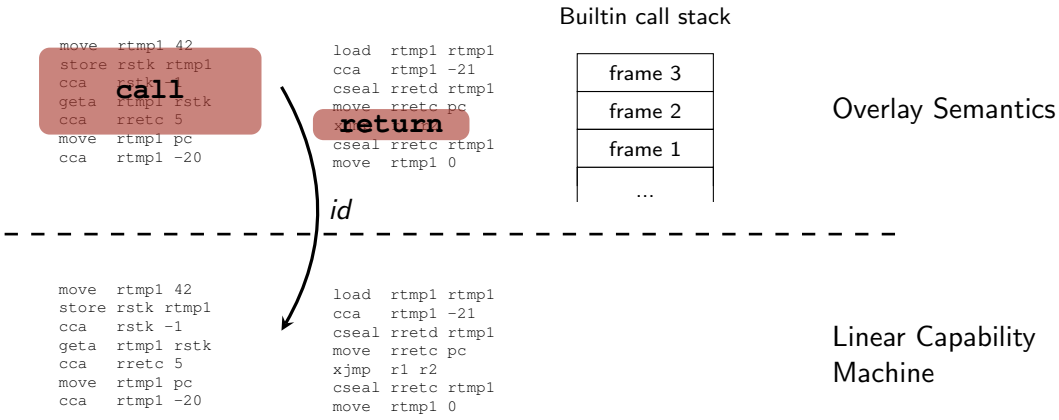
Fully-abstract overlay semantics



Fully-abstract overlay semantics



Fully-abstract overlay semantics

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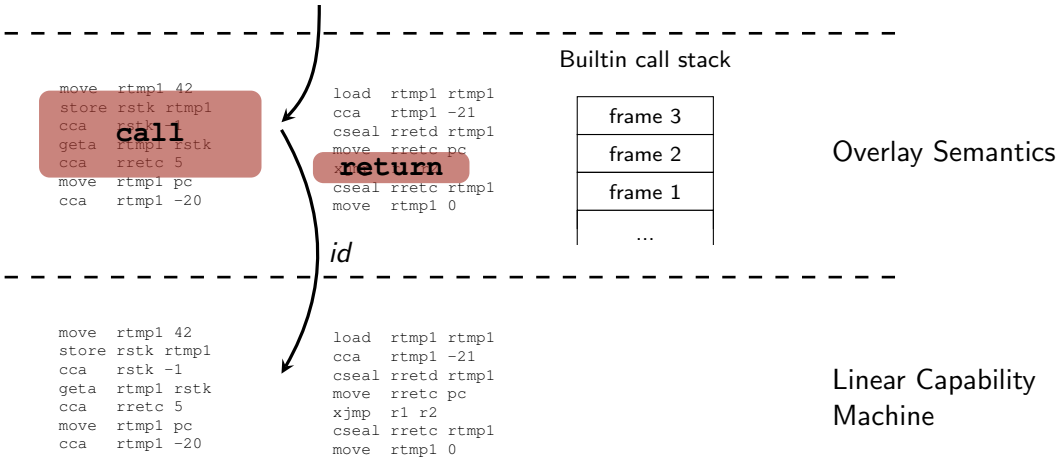
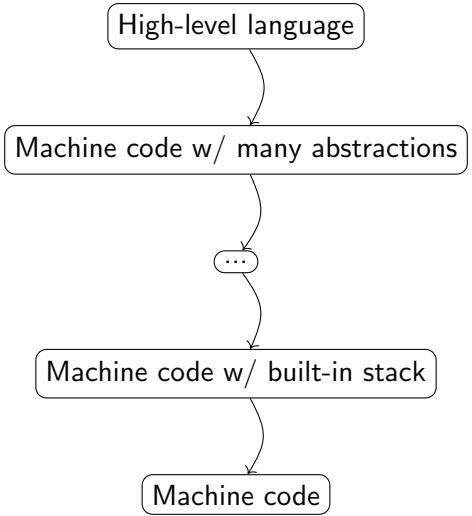
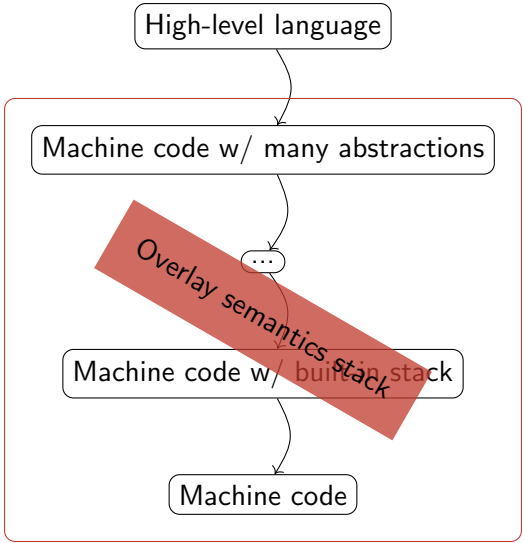


Proof sketch for a realistic secure compiler



Proof sketch for a realistic secure compiler



Paper overview

- LCM: A formalization of a simple CHERI-like capability machine with linear capabilities
- StkTokens, a new calling convention that provably guarantees LSE and WBCF on LCM
- A better way to formalize these guarantees based on a novel technique called *fully-abstract overlay semantics*
- Proof of LSE and WBCF which includes
  - oLCM: an overlay semantics for LCM with built-in LSE and WBCF
  - proving full-abstraction for the embedding of oLCM into LCM by
  - defining and using a cross-language, step-indexed, Kripke logical relation with recursive worlds

Thank you!

StkTokens summary

- Check the base address of the stack capability before and after calls.
- Make sure that local stack frames are non-empty.
- Create token and data return capability on call: split the stack capability in two to get a stack capability for your local stack frame and a stack capability for the unused part of the stack. The former is sealed and used for the data part of the return pair.
- Create code return capability on call: Seal the old program pointer.
- Reasonable use of seals: Return seals are only used to seal old program pointers, every return seal is only used for one call site, and they are not leaked.

StkTokens FAQ

- *Do you support tail calls?*
  - Yes.
- *Do you support higher-order functions?*
  - Yes.