KU LEUVEN

DISTRINET RESEARCH GROUP

Recent Advances in System Software Security

Prof. Frank PIESSENS

SECAPPDEV 2016

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Introduction

- System software is often programmed in C-like languages
  - Another session has covered the security consequences and the raging attacker-defender race
- The purpose of this lecture is to give you a taste of some recent advances in this area:
  - Systems-level compartimentalization mechanisms:
    - We look at protected module architectures like the new Intel SGX
  - Alternative **safe** systems-programming languages:
    - We look at a promising candidate: the Rust language
  - Advanced compiler-based countermeasures:
    - Control-Flow Integrity
    - Pointer-based checking

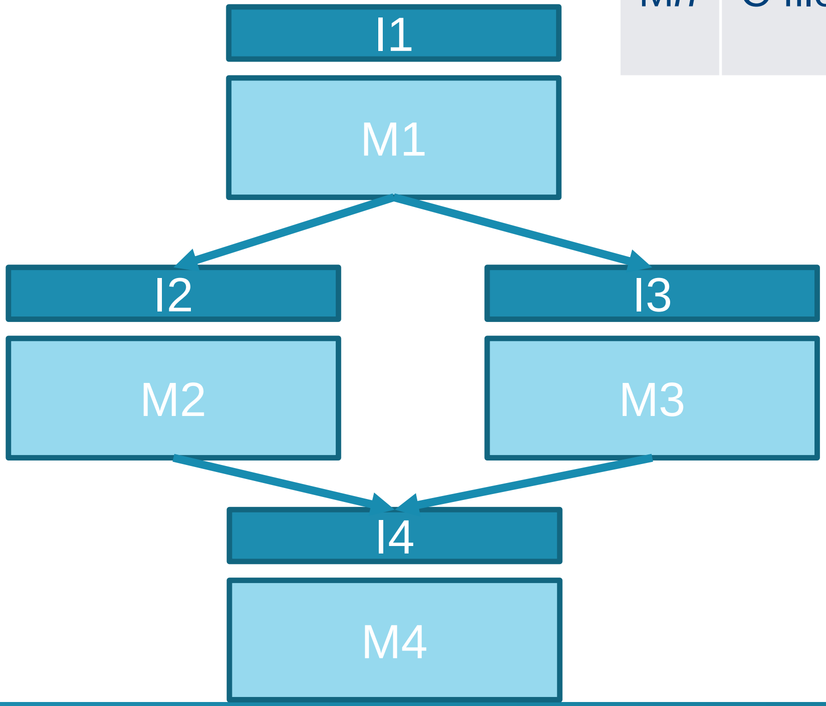
Overview

- Protected module architectures
  - Fine grained isolation at machine code level
  - Supported in the recent Intel Skylake processors under the name Intel Software Guard eXtentions (Intel SGX)
- Safe systems programming languages
  - Compiled languages with low-level control over memory, but with strong safety assurance
  - Supported in the Rust programming language
- Advanced compiler based countermeasures
  - Control-flow integrity (CFI)
  - Pointer-based checking

Problem statement

Consider a program consisting of a number of modules, and their dependencies.

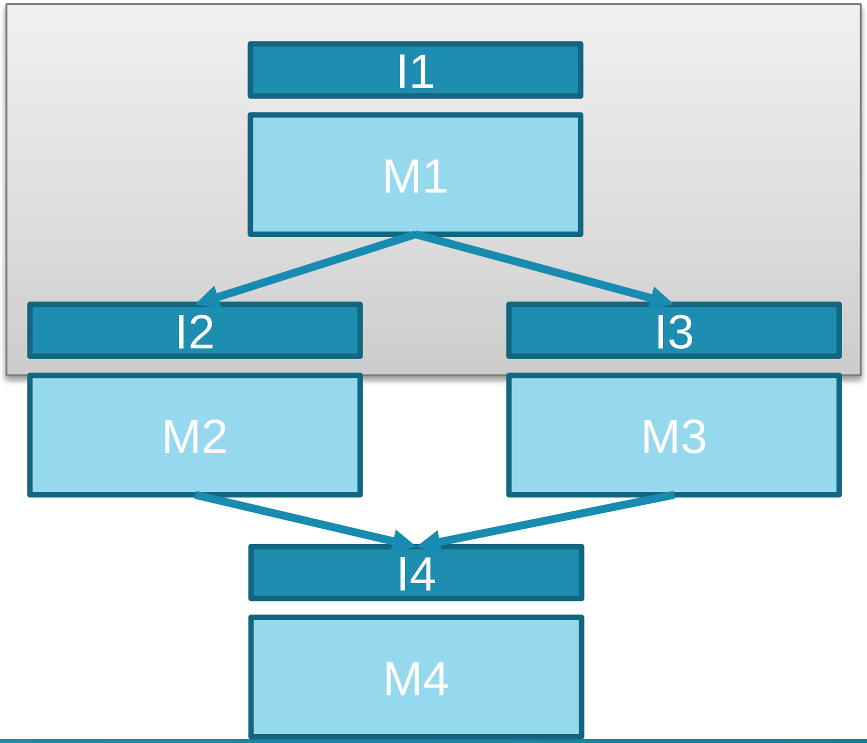
	C	Java	ML
I*n*	Header file	(Roughly) Interfaces	Signature
M*n*	C file	(Roughly) Classes	Structure / Functor



Problem statement

Suppose you have proven a (security) property of module M1 by modular reasoning. E.g.:

- Some invariant holds on the module's state
- Some data in the module remains confidential towards other modules
- The integrity of some data in the module is protected from other modules



Problem statement

Suppose you have proven a (security) property of module M1 by modular reasoning. E.g.:

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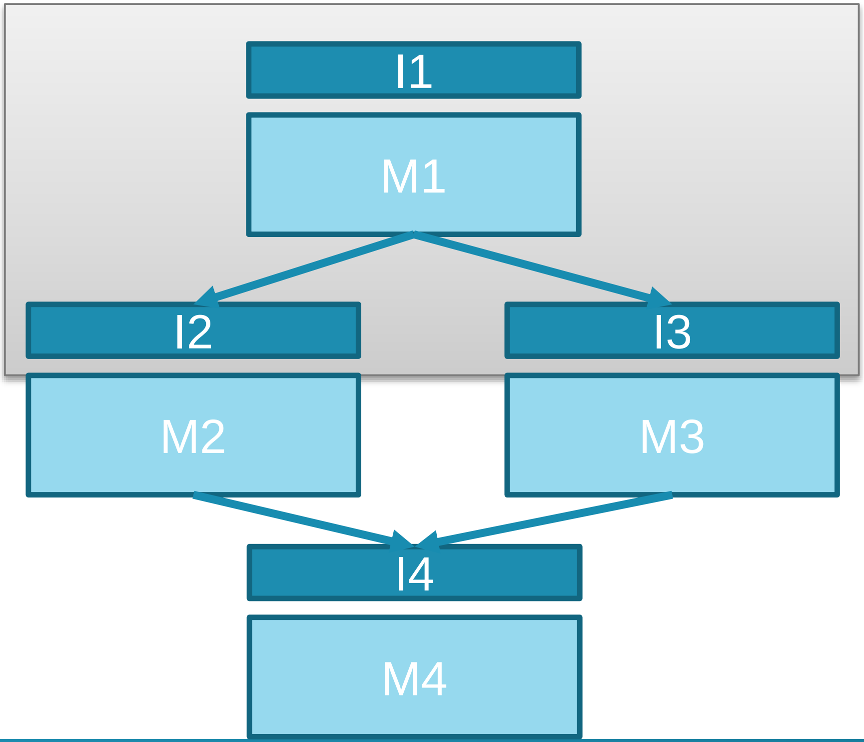


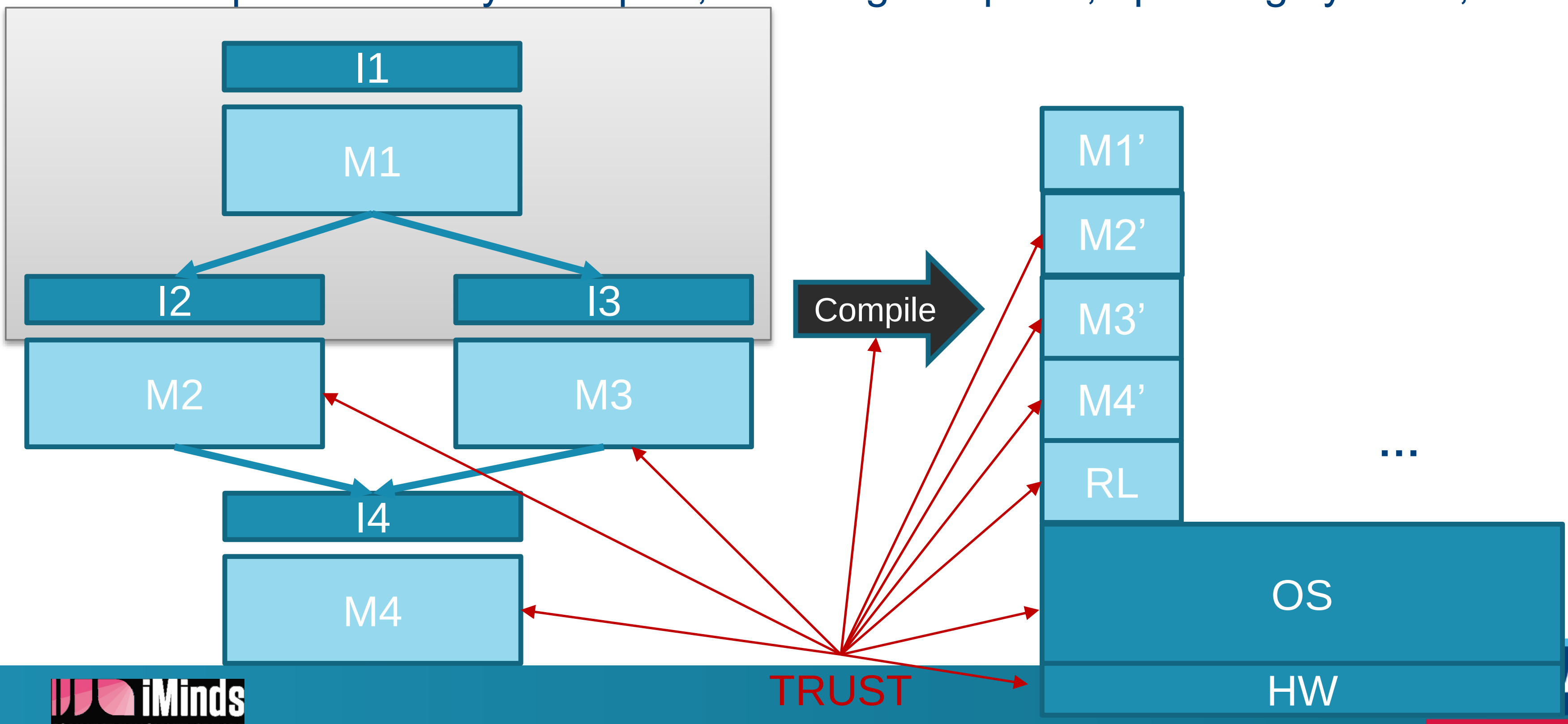
KEY QUESTION:

What do you need to trust to be sure that this property will hold at run time?

Problem statement

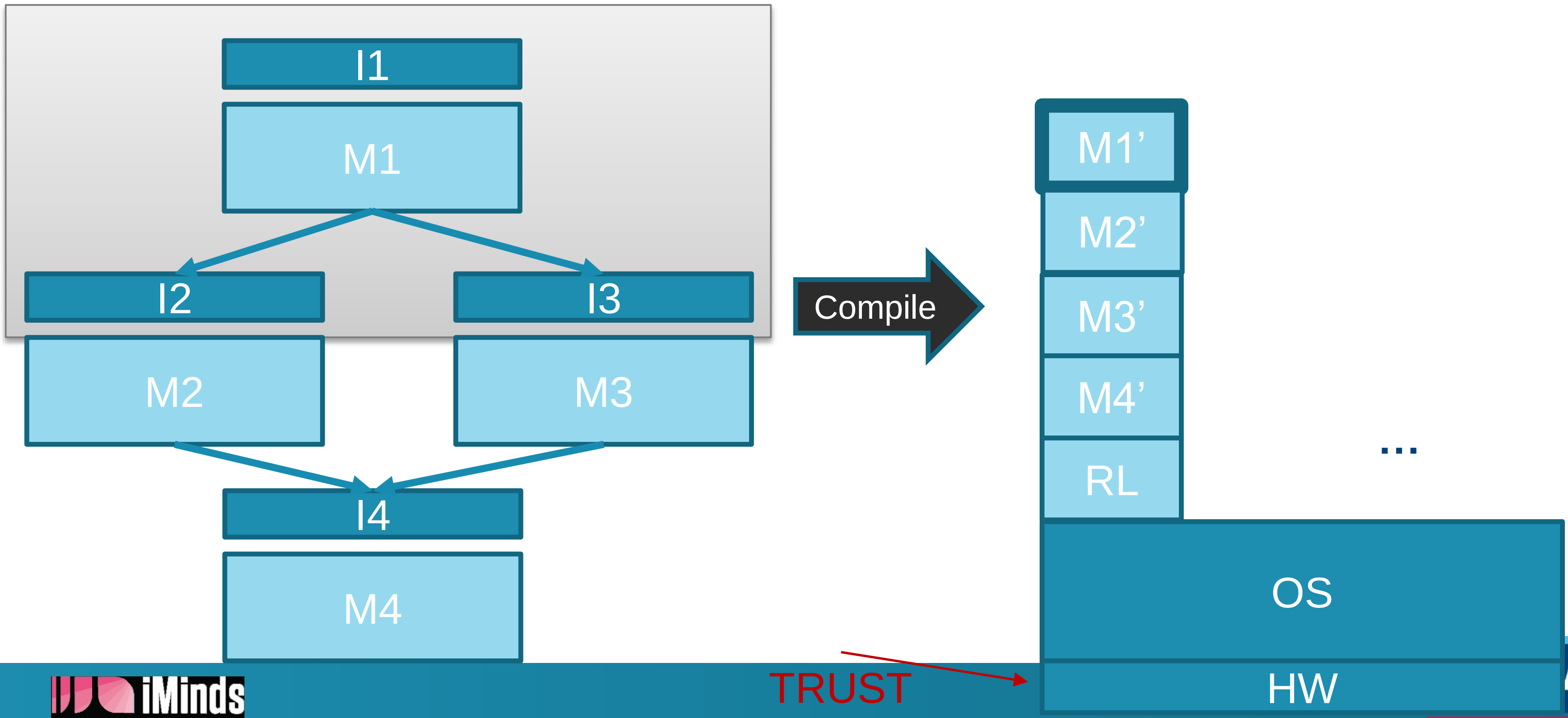
You have to trust at least:

- Your reasoning (e.g. the soundness of the verification tool)
- The implementations of the unverified modules of your program
- The execution infrastructure
  - Potentially “simple” : an interpreter on bare hardware
  - In practice always complex, including compilers, operating systems, …



Problem statement

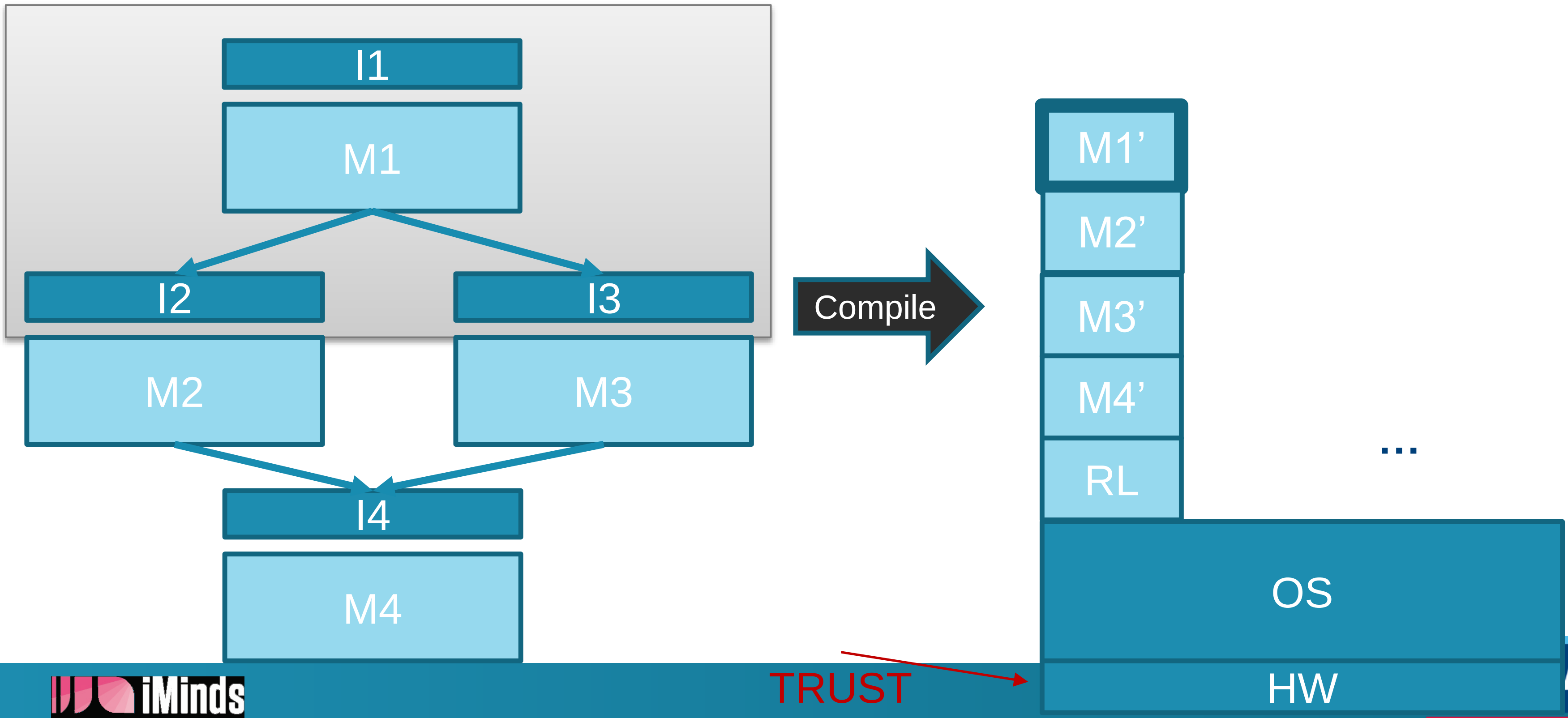
Can we reduce the TCB to just the hardware, while maintaining backward compatibility with legacy OS's and applications?



Problem statement

Focus today only on:

- **The creation and attestation of isolated / protected modules within a legacy system**
  - Job Noorman, Pieter Agten, Wilfried Daniels, Raoul Strackx, Anthony Van Herrewege, Christophe Huygens, Bart Preneel, Ingrid Verbauwhede, Frank Piessens, *Sancus: Low-cost trustworthy extensible networked devices with a zero-software trusted computing base*, USENIX Security 2013



Remember the run-time machine state for executing C programs

```c
void get_request(int fd, char buf[]) {
  read(fd,buf,16);
}

void process(int fd) {
  char buf[16];
  get_request(fd,buf);
  // Process the request (code not shown)
}
void main() {
  int fd ;
  // Initialize server, wait for a connection
  // Accept connection, with file descriptor fd
  // Finally, process the request:
  process(fd);
}
```

(a) Program source code

```
55              push   %ebp                ; save base pointer
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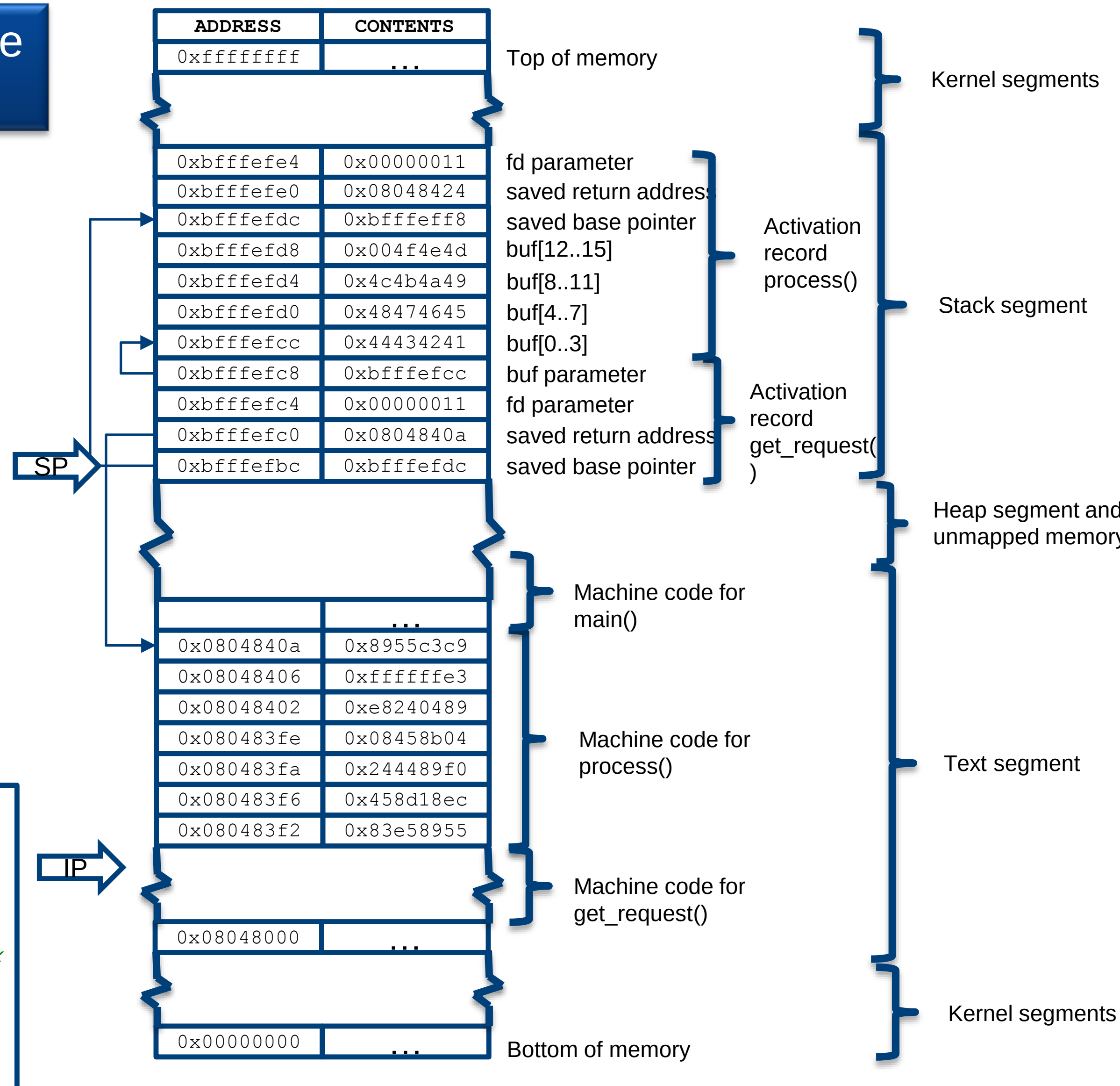
89 44 24 04     mov    %eax,0x4(%esp)      ; and push on the stack
8b 45 08        mov    0x8(%ebp),%eax      ; put fd parameter in %eax
89 04 24        mov    %eax,(%esp)         ; and push on the stack
e8 e3 ff ff ff  call   0x80483ed           ; call get_request
c9              leave                      ; deallocate stack frame
c3              ret                        ; return
```

(b) Machine code for process() function



(c) Run-time machine state on entering get_request()

Using PMA's against memory scraping

secret.h

```
int get_secret(int provided_pin)
```

secret.c

```
static int tries_left = 3;
static int PIN = 1234;
static int secret = 666;

int get_secret(int provided_pin) {
 if (tries_left > 0) {
   if (PIN == provided_pin) {
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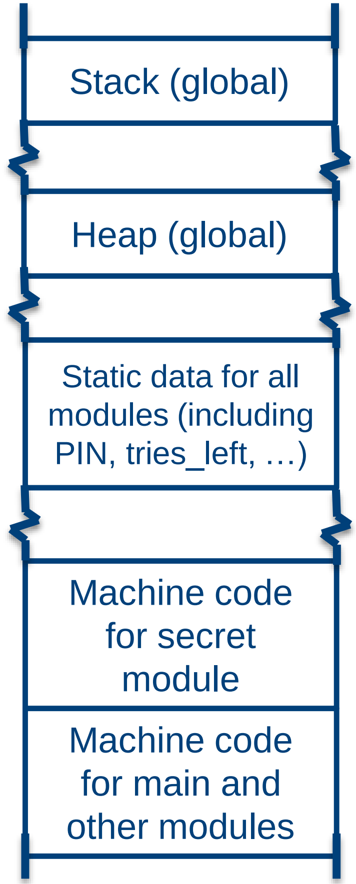
     return secret;}
   else { tries_left-- ; return 0; }; }
else return 0; }
```

(a) The secret module

```
#include<stdio.h>
#include "secret.h"
// includes for other modules

void main() {
// code for main functionality
…
}
```

(b) Other modules of the program



(c) Run-time memory contents

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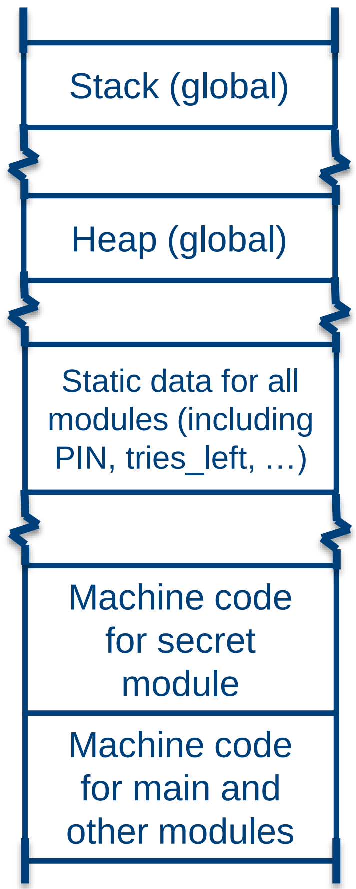

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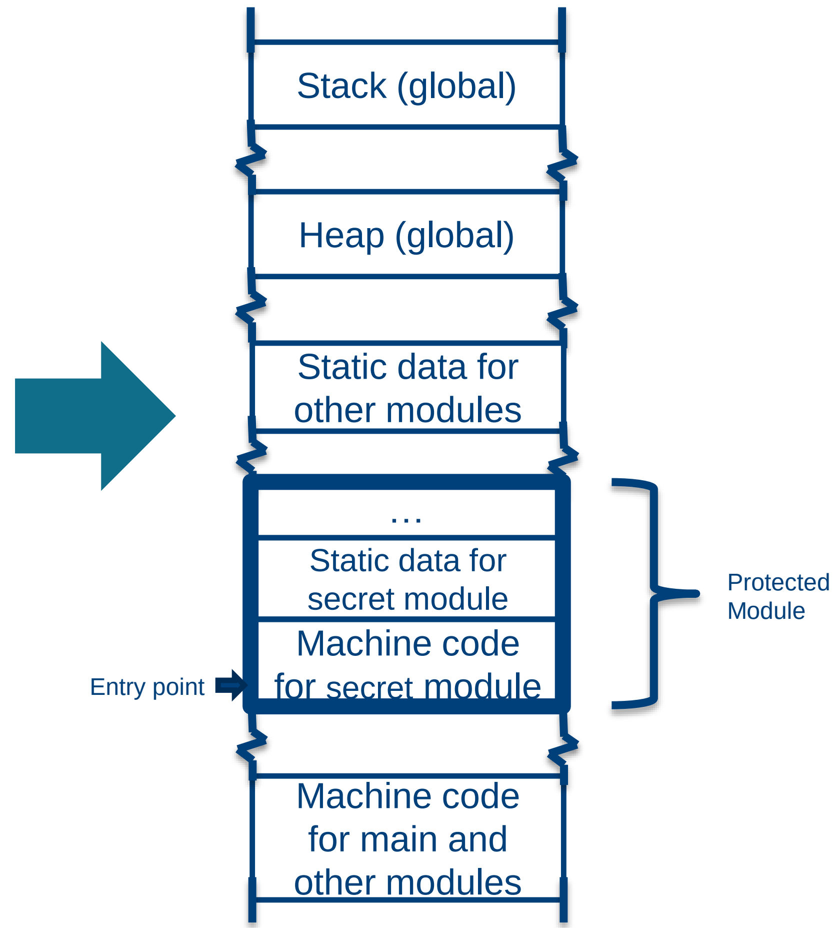
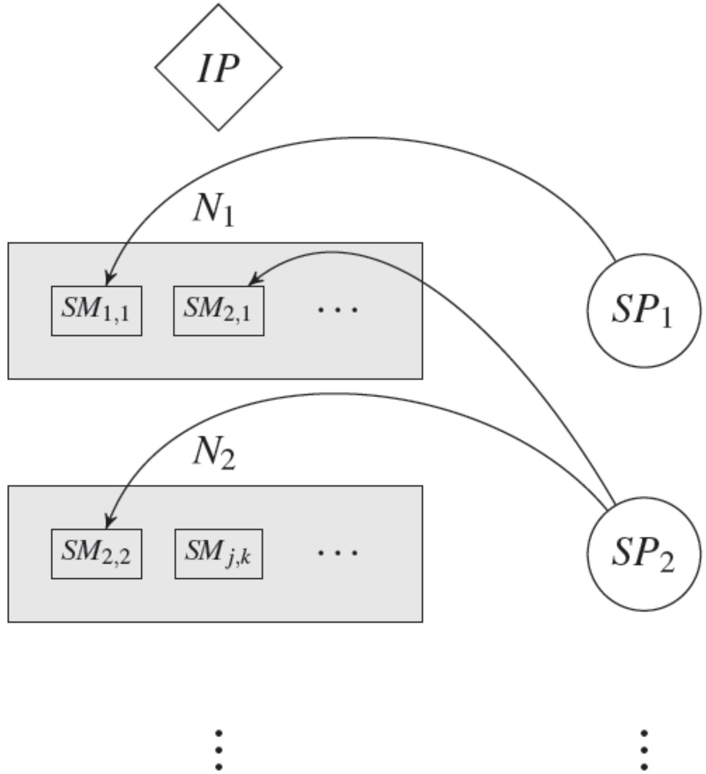


System model

- A network of low-end nodes N managed by an infrastructure provider IP
- Software providers SP deploy software modules SM on these nodes



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Attacker model and security properties

- Attackers can:
  - Manipulate **all** the SW on nodes
  - Control the network as a Dolev-Yao attacker
  - NOT mess with the hardware
- In the presence of such attackers we guarantee:
  - Software module isolation
  - Remote attestation
  - Secure remote communication
  - [Secure linking]

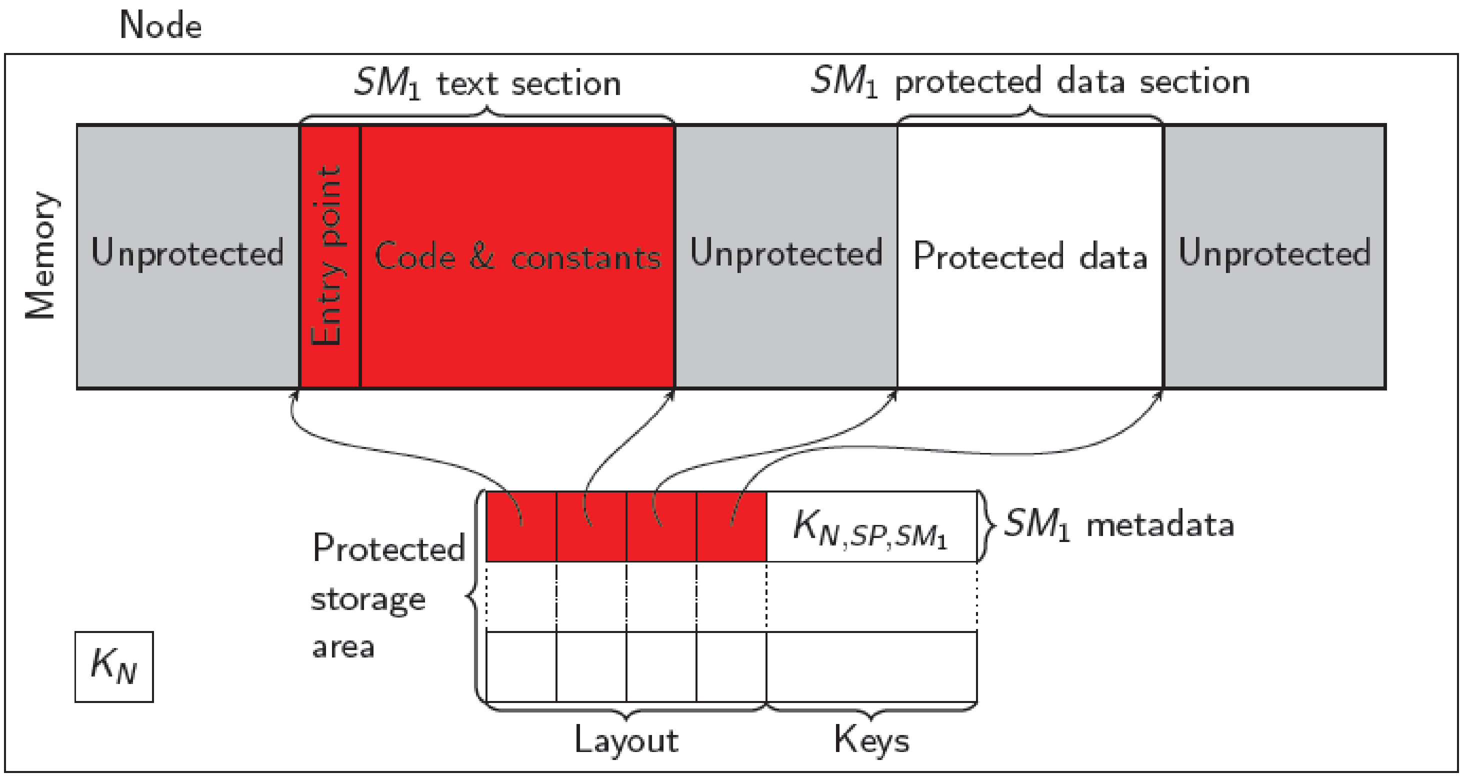
Protected software modules

- Standard SW modules, defining memory sections
  - Public text section
    - Code and constants
  - Private data section
    - Runtime data that needs to be protected
  - Optional unprotected sections
- **Layout** of a module:
  - The load addresses of public and private sections
- **Identity** of a module:
  - Layout + contents of text section

Isolation

- By PC-based access control:

from \ to	*Protected* Entry point	*Protected* Code	*Protected* Data	*Unprotected*
Protected	r x	r x	r w	r w x
Unprotected	x			r w x

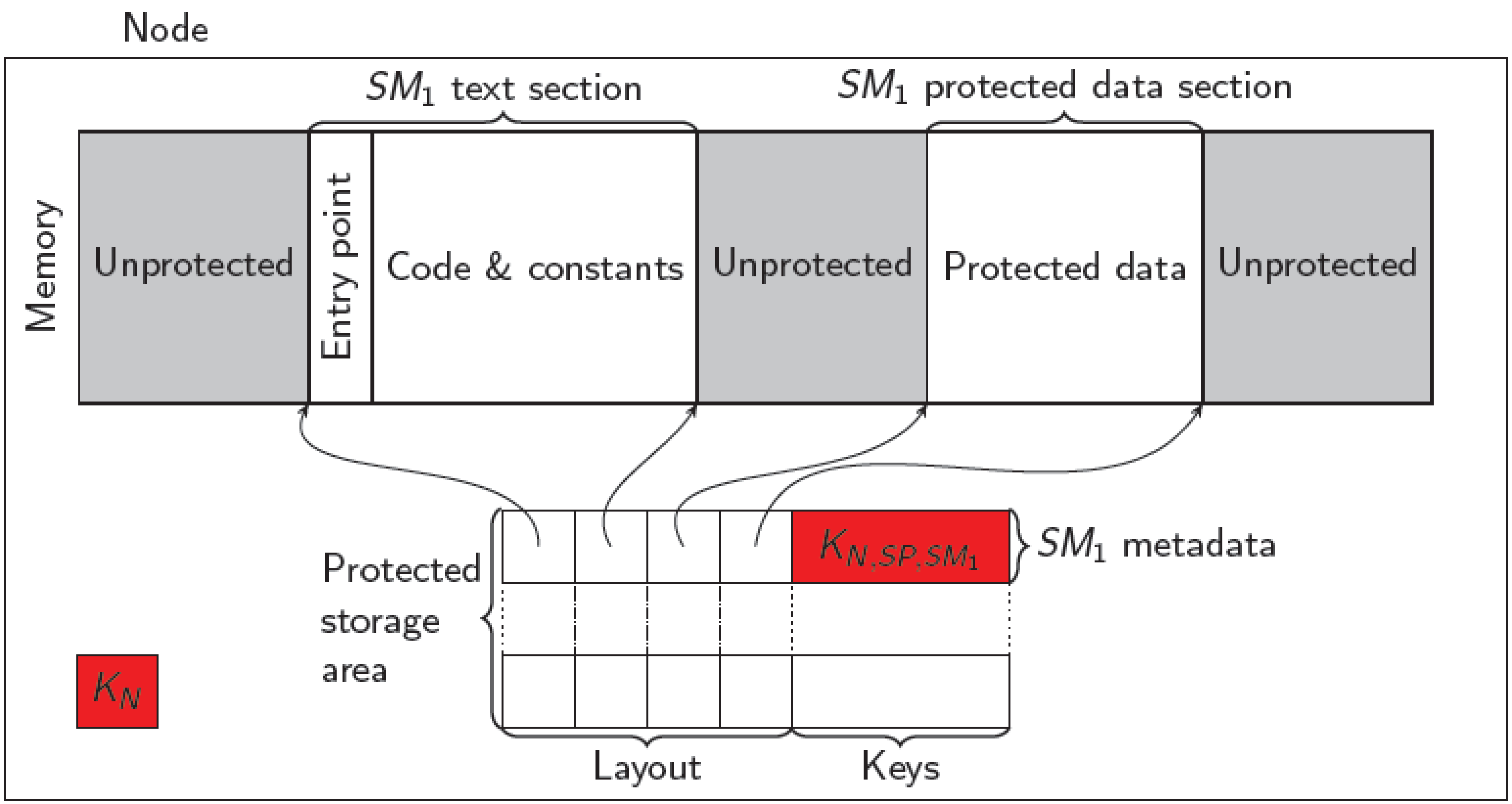


Key management

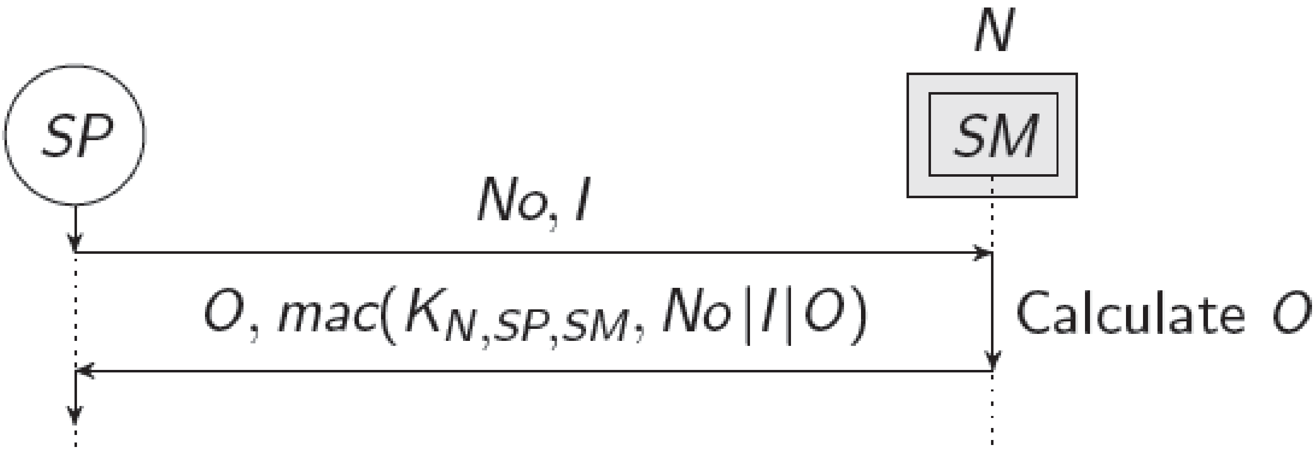
- Strictly symmetric key for performance reasons
- Three types of keys:
  - Node master keys K_N : shared between IP and N
  - Provider keys $K_{N,SP}$: shared between IP, SP and N
  - Module keys $K_{N,SP,SM}$: shared between IP, SP and SM on N
- Nodes are initialized with their master key on production
- All other keys are derived by means of key derivation functions
  - $K_{N,SP} = kdf(K_N, SP)$
  - $K_{N,SP,SM} = kdf(K_{N,SP}, SM)$

Keys on the device managed by HW

- Only computed after enabling isolation
  - **protect** *layout*, SP
- Only usable through special HW instructions
  - **mac-seal** start-address, length, result-address



Remote attestation and secure communication



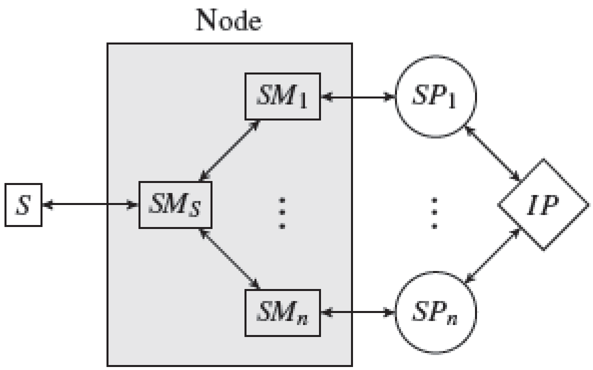
MAC is calculated by a `mac-seal` instruction

Using the key of the calling *SM*

MAC can be recalculated by *SP*. . .

He knows the *correct* $K_{N,SP,SM}$

An example (simplified) scenario



- Node manages a sensor S by means of an IP provided module SM_S
- Various SP's can install SM's:
  1. The SP contacts IP to get a $K_{N,SP}$
  2. SP creates SM, and calculates $K_{N,SP,SM}$
  3. SM is deployed on N using untrusted OS services
  4. SM is protected with the instruction:
     - **protect** *layout*, SP
     - This creates $K_{N,SP,SM}$ and enables memory protection on SM
  5. SP sends a request to SM (including a nonce No)
  6. SM computes a response (possibly calling SM_S and including No) and signs it using the instruction:
     - **MAC-seal**
     - This creates a MAC of the response using $K_{N,SP,SM}$

Some implementation details

- Built as an extension of an open-source MSP430 implementation
- Main changes:
    - Memory access logic that implements PC-based access control
    - Hardware implementations of:
        - HMAC
        - HKDF
        - The Spongent 128/128/8 hash function
    - The new instructions
- Available for download at:
    - https://distrinet.cs.kuleuven.be/software/sancus/

Recap

- Sancus is a low-cost security architecture for networked embedded systems
  - Module isolation though program-counter based access control
  - Key management through a hierarchical symmetric-key ID-based key derivation
  - Remote attestation and secure communication by hardware-guarded access to keys
  - [Secure linking]
  - [A secure compiler supporting the development of modules]
- Intel's recent Skylake processors include a similar security architecture, called Software Guard eXtensions (Intel SGX)

Using PMA’s against memory scraping

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```

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else return 0; }
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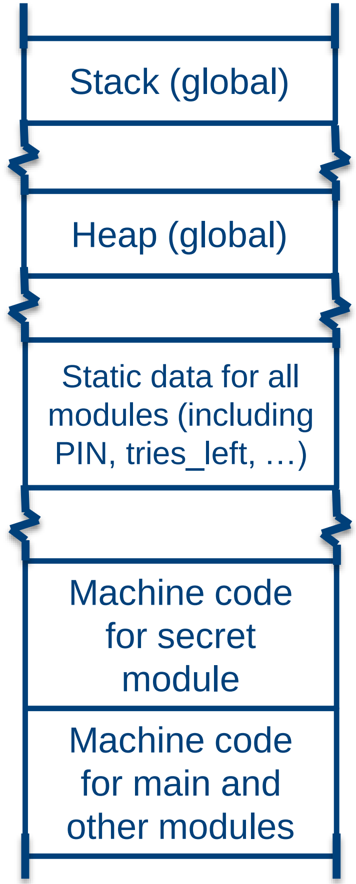

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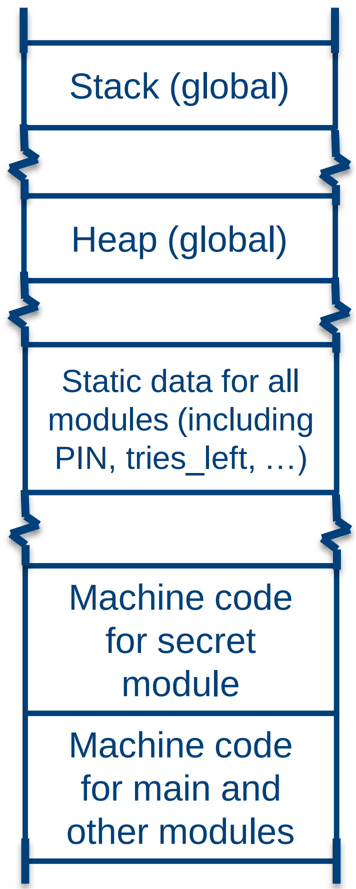

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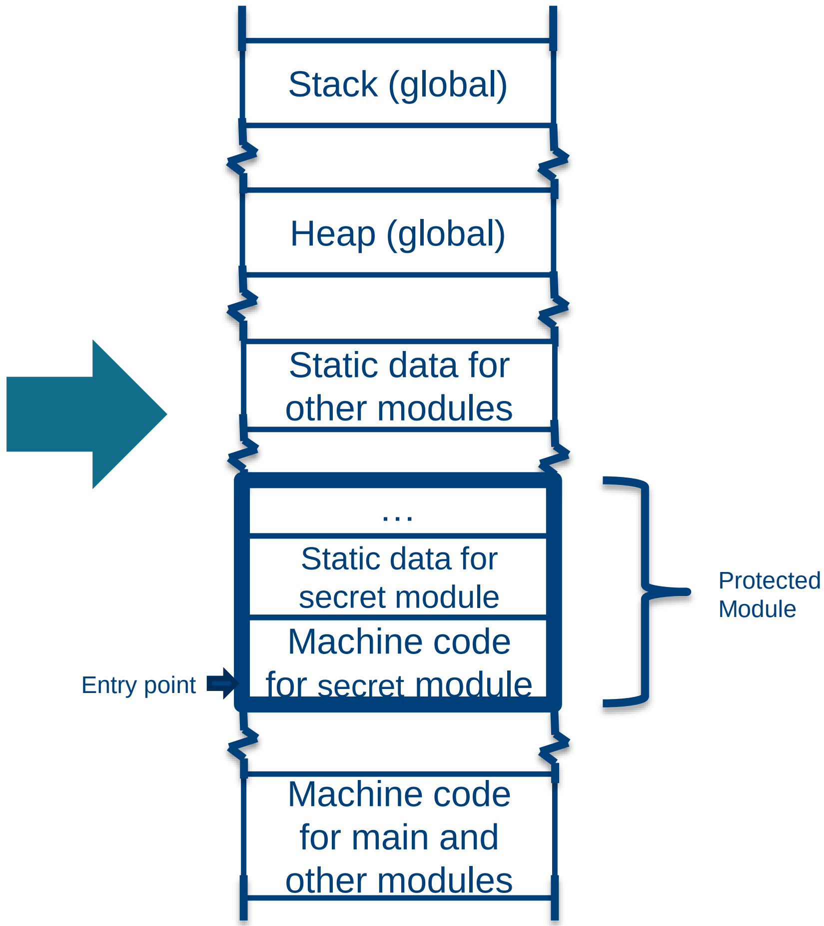

The need for secure compilation

secret.h

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int get_secret(int get_pin())
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secret.c

```
static int tries_left = 3;
static int PIN = 1234;
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int get_secret(int get_pin()) {
 if (tries_left > 0) {
   if (PIN == get_pin()) {
      tries_left = 3;
     return secret;}
   else { tries_left-- ; return 0; }; }
else return 0; }
```

Conclusions

- Protected Module Architectures are a very promising new system security technology
  - They essentially allow the dynamic creation of Trusted Execution Environments (TEEs) within a legacy, untrusted infrastructure.
- But many interesting questions remain:
  - Secure compilation to such architectures
  - Providing secure persistent storage
  - Making sure attackers can not use them to hide malware
  - …

Overview

- Countermeasures of the future:
  - Protected module architectures
    - Fine grained isolation at machine code level
    - Supported in the most recent Intel Skylake processors under the name Intel Software Guard eXtentions (Intel SGX)
  - Safe systems programming languages
    - Compiled languages with low-level control over memory, but with strong safety assurance
    - Supported in the Rust programming language
  - Advanced compiler based countermeasures
    - Control-flow integrity (CFI)
    - Pointer-based checking

The trade-off between safety and low-level control

- From a security point of view, safe languages like Java, C#, Scala, … are **significantly** better
- Why has C not disappeared?
- There are several reasons for this:
  - C is very “light-weight”
    - Very good performance
    - But also: no need for a “runtime” or “virtual machine”
  - C gives the programmer control over low-level details
    - What is allocated on stack versus heap
    - How are data structures laid out in memory
- Rust is a new contender in this arena

Documentation Community Downloads Contribute

Recommended Version:
1.6.0 (Windows installer)

Install

Other Downloads

Rust is a systems programming language that runs blazingly fast, prevents segfaults, and guarantees thread safety.

Show me!

Featuring

- zero-cost abstractions
- move semantics
- guaranteed memory safety
- threads without data races
- trait-based generics
- pattern matching
- type inference
- minimal runtime
- efficient C bindings

```
// This code is editable and runnable!
fn main() {
    // A simple integer calculator:
    // `+` or `-` means add or subtract by 1
    // `*` or `/` means multiply or divide by 2

    let program = "+ + * - /";
    let mut accumulator = 0;

    for token in program.chars() {
        match token {
            '+' => accumulator += 1,
            '-' => accumulator -= 1,
            '*' => accumulator *= 2,
            '/' => accumulator /= 2,
            _ => { /* ignore everything else */ }
        }
    }

    println!("The program \"{}\" calculates the value {}",
              program, accumulator);
}
```

Run

Our focus

- Rust has many interesting features
- But we focus on its most innovative / most complex feature:
  - Ownership and borrowing
- This is an important new approach to avoiding temporal memory safety errors without garbage collection
- It also addresses important concurrency related errors, but we do not focus on this

What part of memory should be writable by the program?

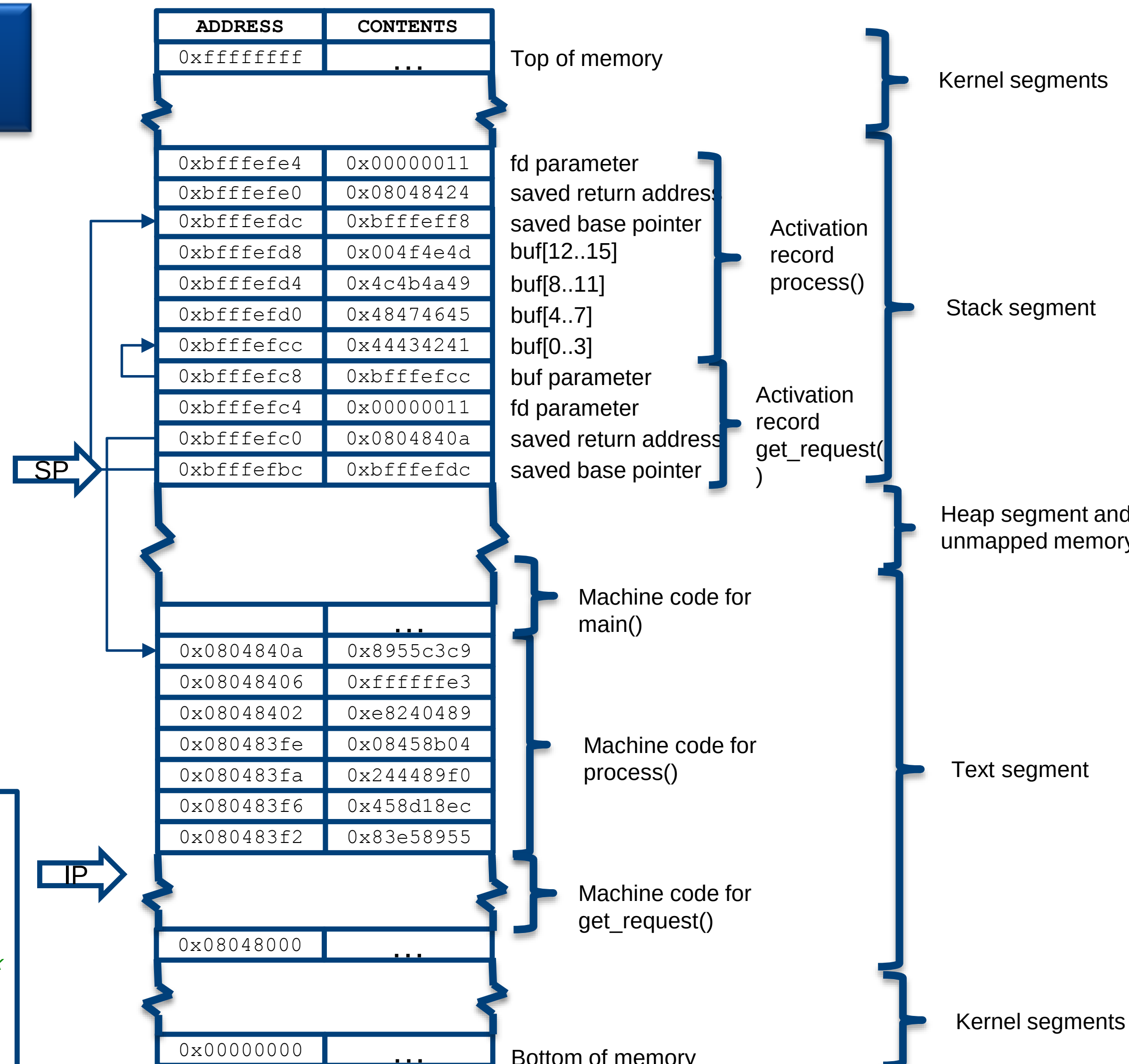
```
void get_request(int fd, char buf[]) {
  read(fd,buf,16);
}

void process(int fd) {
  char buf[16];
  get_request(fd,buf);
  // Process the request (code not shown)
}
void main() {
  int fd ;
  // Initialize server, wait for a connection
  // Accept connection, with file descriptor fd
  // Finally, process the request:
  process(fd);
}
```

(a) Program source code

```
55              push   %ebp                 ; save base pointer
89 e5           mov    %esp,%ebp            ; set new base pointer
83 ec 18        sub    $0x18,%esp           ; allocate stack record
8d 45 f0        lea    -0x10(%ebp),%eax     ; put buf in %eax
89 44 24 04     mov    %eax,0x4(%esp)       ; and push on the stack
8b 45 08        mov    0x8(%ebp),%eax       ; put fd parameter in %eax
89 04 24        mov    %eax,(%esp)          ; and push on the stack
e8 e3 ff ff ff  call   0x80483ed            ; call get_request
c9              leave                       ; deallocate stack frame
c3              ret                         ; return
```

(b) Machine code for process() function



(c) Run-time machine state on entering get_request()

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}

void process(int fd) {
  char buf[16];
  get_request(fd,buf);
  // Process the request (code not shown)
}
void main() {
  int fd = 0x11;
  // Initialize server, wait for a connection
  // Accept connection, with file descriptor fd
  // Finally, process the request:
  process(fd);
}
```

(a) Program source code

```
55              push   %ebp               ; save base pointer
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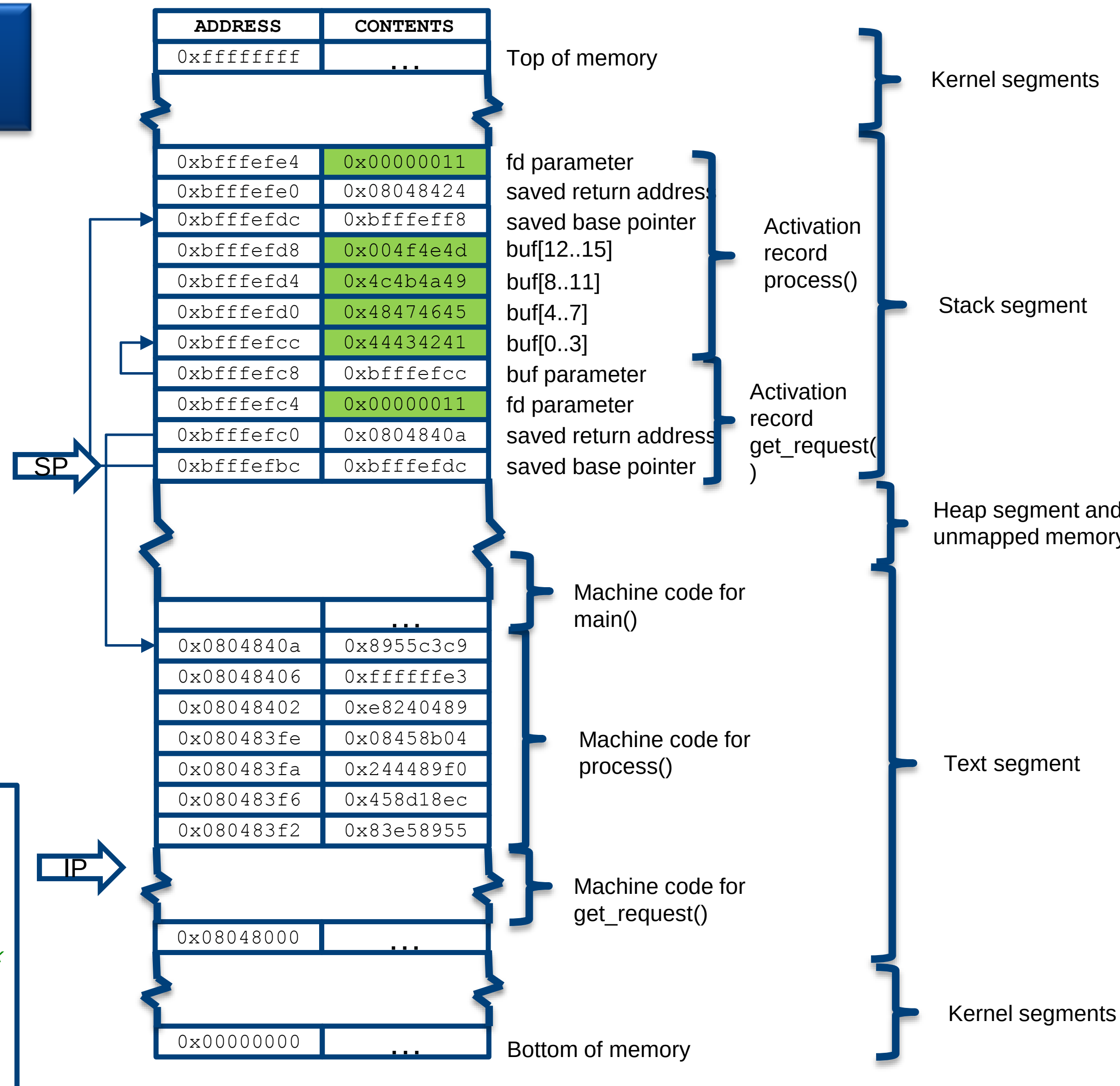

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Essentially, only 4 ways things can go wrong

- **Spatial memory safety errors**: a blob of allocated memory is accessed out of bounds
- **Temporal memory safety errors**: a blob of memory is accessed after it has been deallocated
- **Pointer forging**: creating an invalid pointer value
  - By invalid casts
  - By use of uninitialized memory
- **Unsafe primitive API functions**:
  - Like C's printf() function

Spatial memory safety

- Examples: indexing an array, indexing a struct, pointer arithmetic

```
void f1(int a[]) {
    a[5] = 10;
}

void f2(int *a) {
    *(a+5) = 10;
}
```

```
struct S {
    int x;
    int y; };

void f3(struct S p) {
    p.x = 20;
}
```

- How could the compiler protect against spatial memory safety errors?

Enforcing spatial memory safety

- Through type checking for structs and arrays with statically known bounds
  - E.g. Java type system will make sure that you can not access a non-existing field of an object
- Through run-time bounds checking otherwise
  - E.g. Java throws ArrayIndexOutOfBoundsException
  - E.g. “Fat” pointers in C or C++

Temporal memory safety

- How long are pointers valid?
  This depends on how the pointer is created.

```c
int c;

int* f(int x) {
    int i;
    int *p1 = &c;
    int *p2 = malloc(sizeof(int));
    int *p3 = &x;
    int *p4 = &i;

    return p1; // or p2? or p3? or p4?
}
```

A simple example

```c
typedef struct  {
    int len;
    int cap;
    int* data;
} vec;

vec newvec() {
    vec v;
    v.len = 0;
    v.cap = 2;
    v.data = malloc(2*sizeof(int));
    return v;
}

void push(vec* v, int i) {
    if (v->len >= v->cap) {
        v->cap *= 2;
        int *new = malloc(v->cap * sizeof(int));
        memcpy(new,v->data, v->len * sizeof(int));
        free(v->data);
        v->data = new;
    }
    v->data[v->len++] = i;
}
```

```c
void printvec(vec v) {
    int i;
    for (int i = 0; i < v.len; i++) {
        printf("%d\n", v.data[i]);
    }
}

int* get(vec* v, int i) {
    return v->data + i;
}

void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0); *i0 = 10;
    printvec(v);
    for (i = 1; i < 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

A simple example

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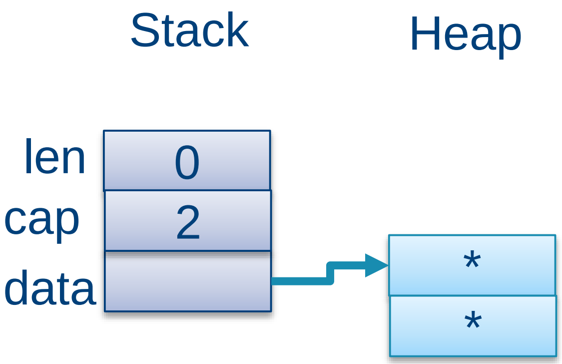

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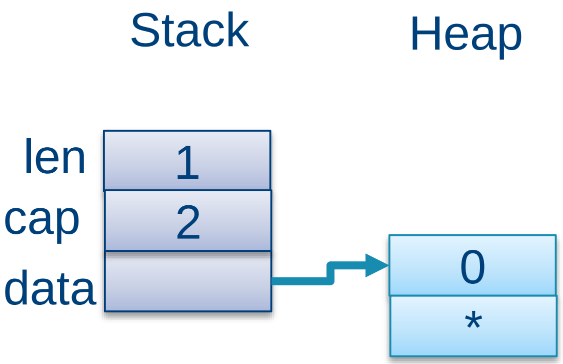
}
```



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void main() {
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    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0); *i0 = 10;
    printvec(v);
    for (i = 1; i < 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

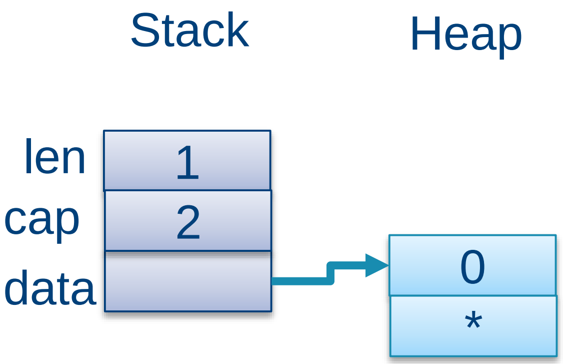

Output:
0

A simple example

```
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0); *i0 = 10;
    printvec(v);
    for (i = 1; i < 4; i++) push(&v,i);
    printvec(v);
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}
```
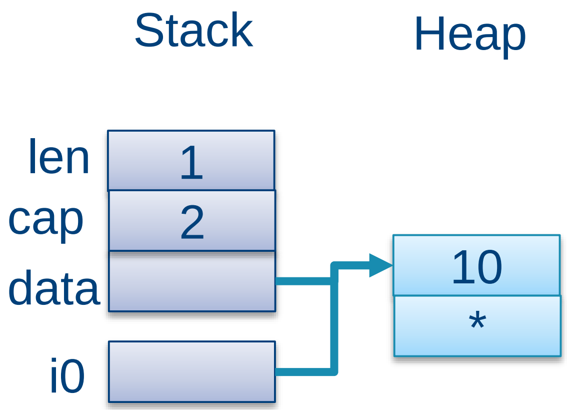
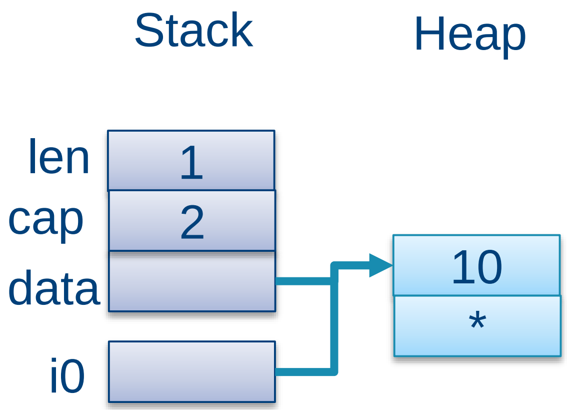



Output:
0

A simple example

```
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0); *i0 = 10;
    printvec(v);
    for (i = 1; i < 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

Output:
0
10



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    int i;
    push(&v,0);
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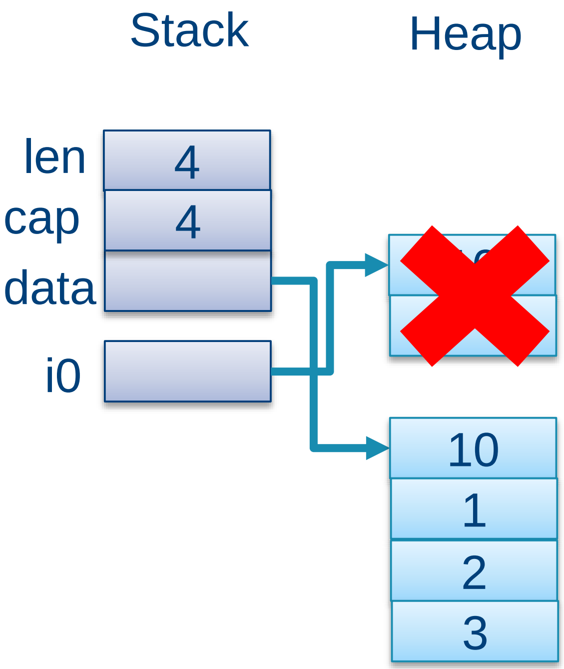
    printvec(v);
    for (i = 1; i < 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

Output:
0
10



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```
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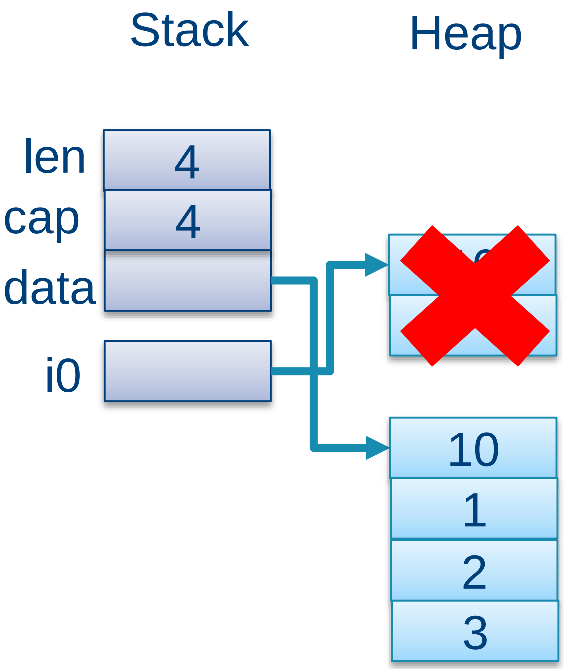
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0); *i0 = 10;
    printvec(v);
    for (i = 1; i < 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

Output:
0
10
10
1
2
3



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}
```
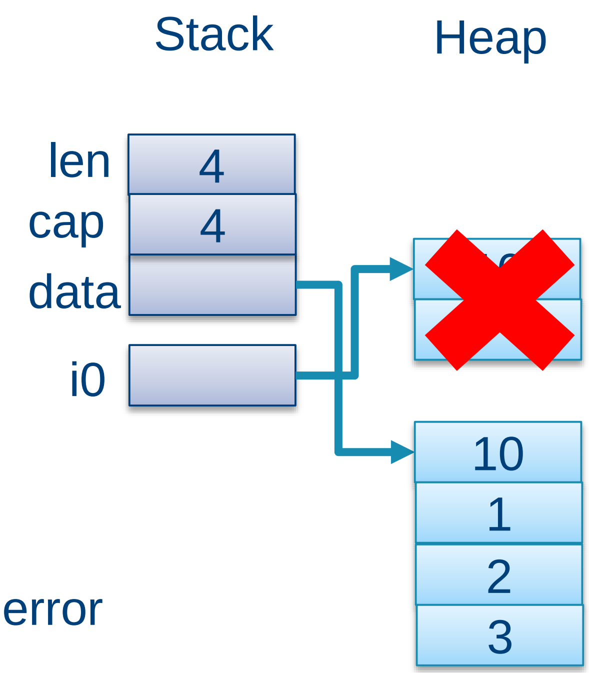
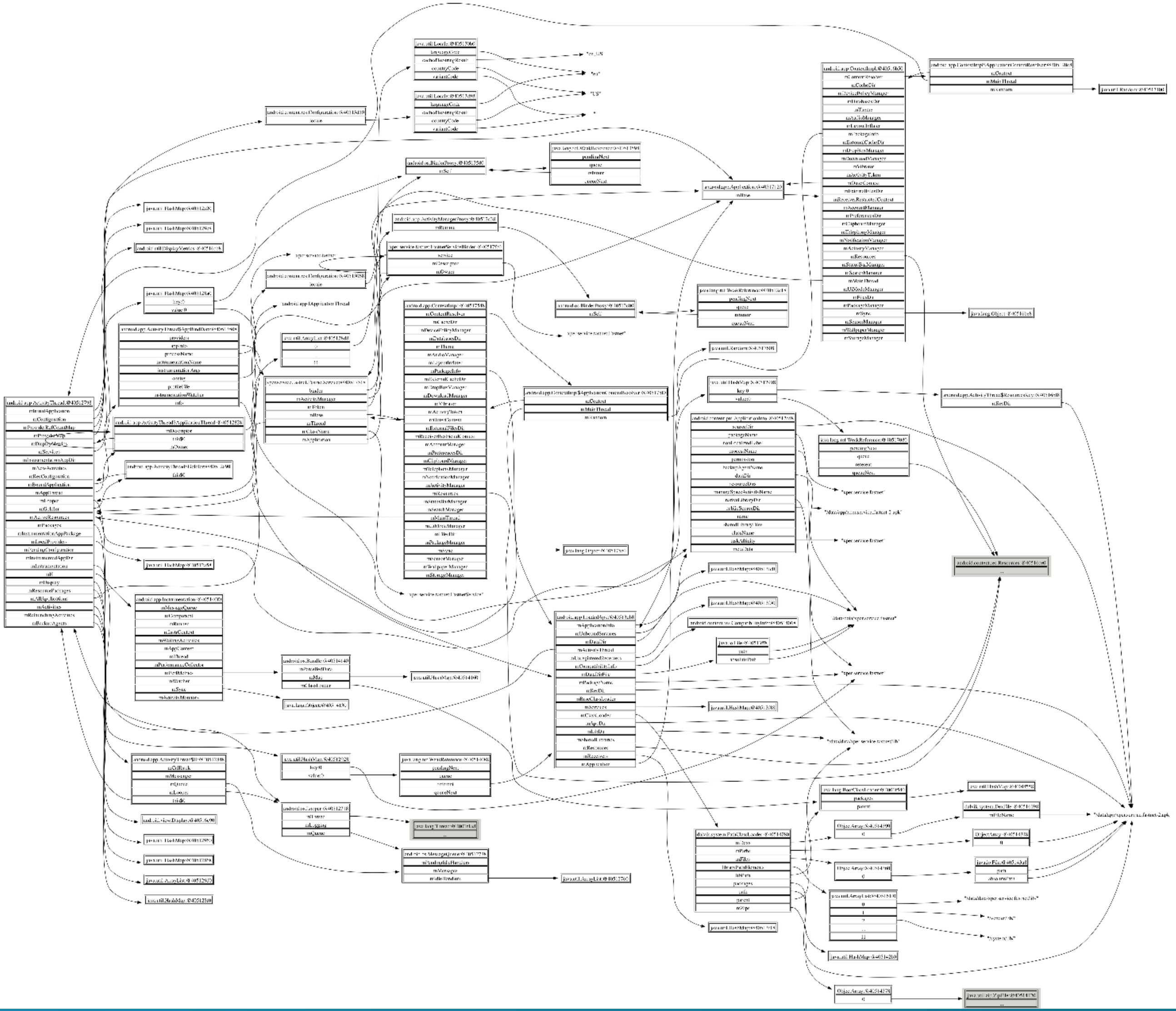

Temporal memory safety error



Output:
0
10
10
1
2
3

Real heap looks more complicated…



Enforcing temporal memory safety

- Allocate everything on the heap, and do **garbage collection**:
  - Programmer can not do explicit deallocation
    - I.e. no free()
  - At regular intervals, the program will be halted and the run-time system will clean up unused memory
    - Basic idea: check what memory is reachable from the current program state, and deallocate all the rest
    - Many different strategies to implement this with different pros and cons
- Important disadvantages for systems programming:
  - Less precise control over memory
  - Unpredictable timing

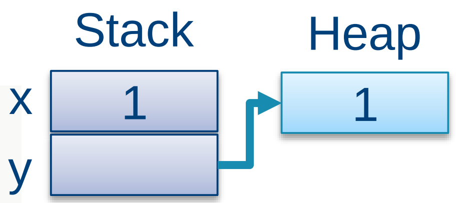
Enforcing temporal memory safety

- New approach: **ownership types** and **borrowing**
- Basic idea:
  - There is at all times a unique **owning** pointer to each allocated blob of memory
  - Memory is deallocated when the owning pointer disappears
    - Because it goes out of scope
    - Or because it is overwritten
    - Or because it was part of a data structure that is being deallocated
- We discuss the implementation of this idea in **Rust**

Memory management in Rust

- Programmer controls:
  - At what time memory is allocated
  - And where it is allocated (stack / heap)
- Deallocated when owner goes out of scope

```rust
fn main() {
    let x = 1; // allocated on the stack
    let y = Box::new(1); // allocated on the heap
}
```



No use after free is possible

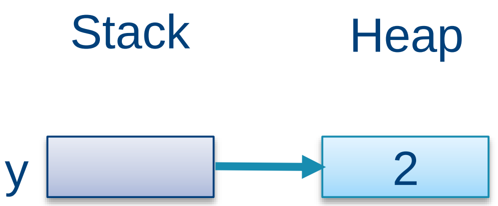
- There was only a single pointer, and it has gone out of scope

```
fn main() {

 {
 let x = Box::new(1);    // alloc x
 println!("x = {}", *x);
 }                        // free x
// ERROR: println!("x = {}", *x);
}
```

Move semantics

- Pointers are not copied but **moved**

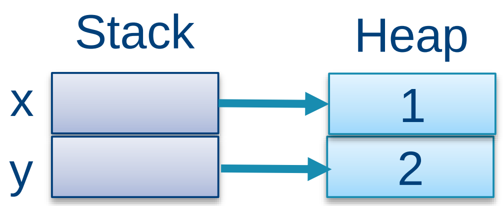
```
fn main() {

let mut y = Box::new(2);

 {
 let x = Box::new(1);
 println!("x = {}", *x);
 y = x;
 // ERROR: println!("x = {}", *x);
 }

println!("y = {}", *y);
}
```



Move semantics

- Pointers are not copied but **moved**

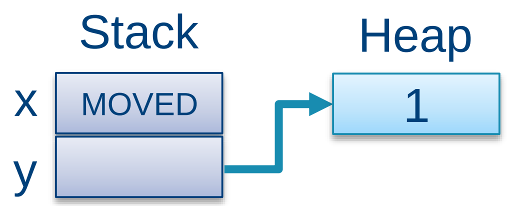
```
fn main() {

let mut y = Box::new(2);

 {
 let x = Box::new(1);
 println!("x = {}", *x);
 y = x;
 // ERROR: println!("x = {}", *x);
 }

println!("y = {}", *y);
}
```



Move semantics

- Pointers are not copied but **moved**

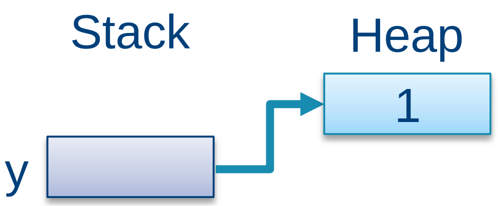
```
fn main() {

let mut y = Box::new(2);

 {
 let x = Box::new(1);
 println!("x = {}", *x);
 y = x;
 // ERROR: println!("x = {}", *x);
 }

println!("y = {}", *y);
}
```



Move semantics

- Pointers are not copied but **moved**
  - Hence: there is always a **unique** owning pointer

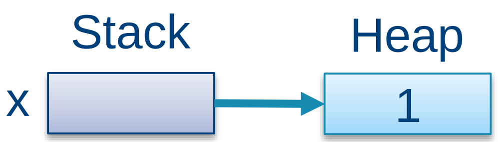
```
fn main() {

let mut y = Box::new(2);

 {
 let x = Box::new(1);
 println!("x = {}", *x);
 y = x;
 // ERROR: println!("x = {}", *x);
 }

println!("y = {}", *y);
}
```



Pointers move into functions too

- Ownership moves from argument to formal parameter
- So when is the allocated memory freed in the program below?

```
fn main() {
    let x = Box::new(1);
    println!("x = {}", *x);
    f(x);
    // ERROR: println!("x = {}", *x);
}

fn f(y : Box<i32>) {
    println!("y = {}", *y);
}
```



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    f(x);
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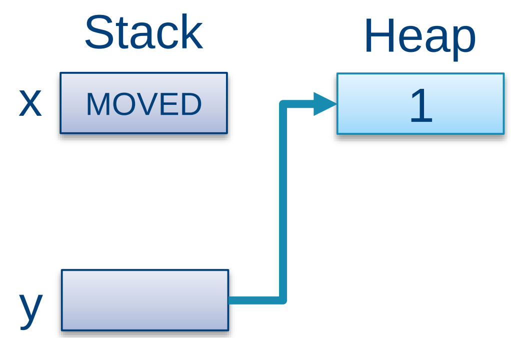

Pointers move into functions too

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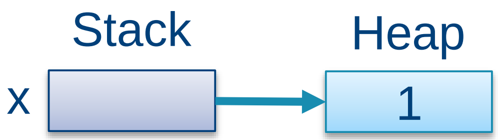
```
fn main() {
    let x = Box::new(1);
    println!("x = {}", *x);
    f(x);
    // ERROR: println!("x = {}", *x);
}

fn f(y : Box<i32>) {
    println!("y = {}", *y);
}
```

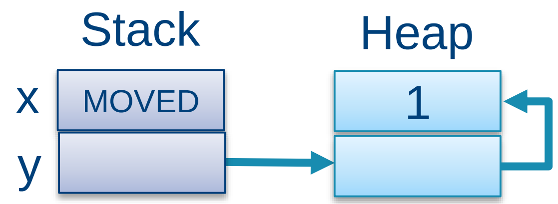
Pointers can also move into Boxes and structs

```
fn main() {
  let mut x = Box::new(1);
  let mut y = Box::new(x);
  let mut z = Box::new(y);
  println!("Val:{}",***z);
}
```



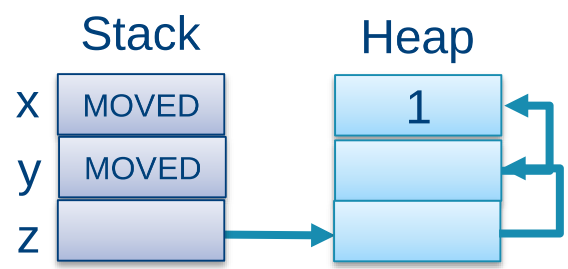
Pointers can also move into Boxes and structs

```
fn main() {
  let mut x = Box::new(1);
  let mut y = Box::new(x);
  let mut z = Box::new(y);
  println!("Val:{}",***z);
}
```



Pointers can also move into Boxes and structs

```
fn main() {
  let mut x = Box::new(1);
  let mut y = Box::new(x);
  let mut z = Box::new(y);
  println!("Val:{}",***z);
}
```



Enforcing unique ownership simplifies the heap

- The heap is a forest (set of trees), with allocated blobs of memory as nodes, and owning references as arrows.
- Roots of the trees are on the stack:
  - local variables of Box type
- If a local variable goes out of scope, that tree gets deallocated
  - We know that there are no other owners, because of uniqueness of ownership
- Uniqueness of ownership is maintained with the move semantics of pointers

Borrowing

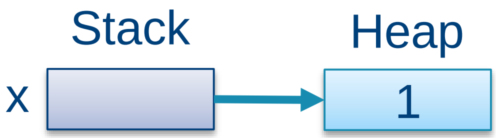
- Move semantics is sometimes too limiting / annoying

```
fn main() {
  let mut x = Box::new(1);
  print(x);
  *x = 2;            <- ERROR
  print(x);
}

fn print(y:  Box<i32>) {
  println!("Value:{}", *y);
}
```

- Rust supports “borrowing” of references to address this

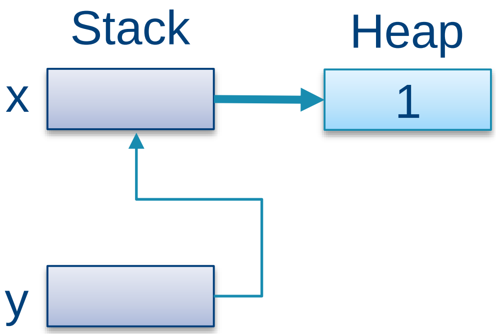
Borrowing

```
fn main() {
 let mut x = Box::new(1);
 print(&x);
 *x = 2;
 print(&x);
 }

fn print(y: &Box<i32>) {
 println!("Value: {}", **y);
}
```



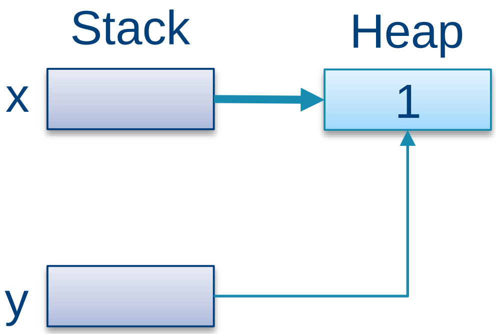
Borrowing

```
fn main() {
 let mut x = Box::new(1);
 print(&x);
 *x = 2;
 print(&x);
 }

fn print(y: &Box<i32>) {
 println!("Value: {}", **y);
}
```



Borrowing

```
fn main() {
  let mut x = Box::new(1);
  print(& *x);
  *x = 2;
  print(& *x);
}

fn print(y:  &i32) {
  println!("Value:{}", *y);
}
```



Borrowing rules

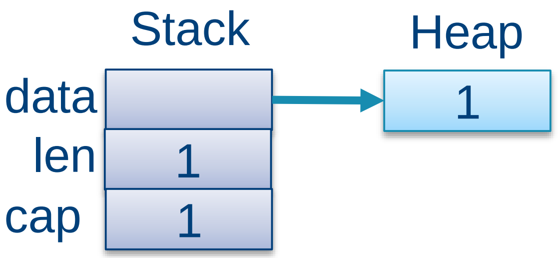
- To avoid introducing temporal safety errors, borrowing and ownership follow some rules:
  - The *lifetime* of a borrow should always be included in the lifetime of the owner from which it is borrowed
    - Otherwise, if the owner dies, the borrowed reference would be dangling

```rust
fn main() {
  let mut x = Box::new(1);
  let mut y = &x;
  {
   let mut z = Box::new(2);
   y = &z;
   }
}
```

```
6:9: 6:10 error: `z` does not live long enough
6     y = &z;
          ^
```

Borrowing should also forbid mutation

```
fn main() {
 let mut vec = Vec::new();
 vec.push(1);
 let first = &vec[0];
 // ERROR: vec.push(2);
 println!("{}", *first);
 }
```



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fn main() {
 let mut vec = Vec::new();
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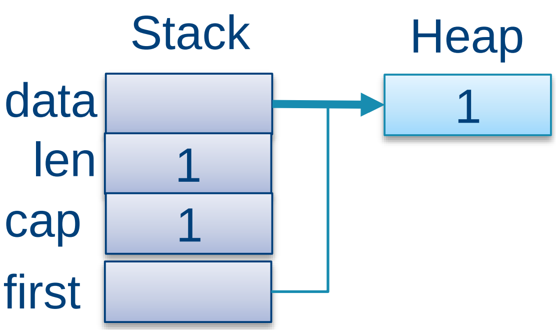
 // ERROR: vec.push(2);
 println!("{}", *first);
 }
```



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 let mut vec = Vec::new();
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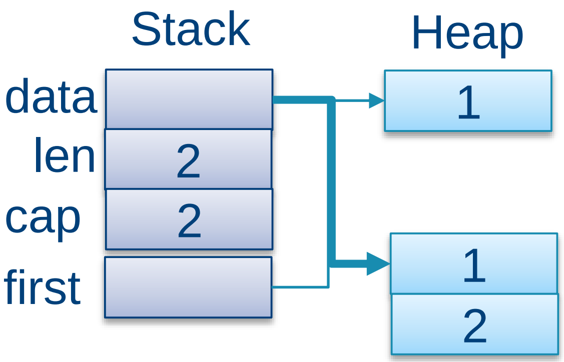
 println!("{}", *first);
 }
```



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 let mut vec = Vec::new();
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 let first = &vec[0];
 // ERROR: vec.push(2);
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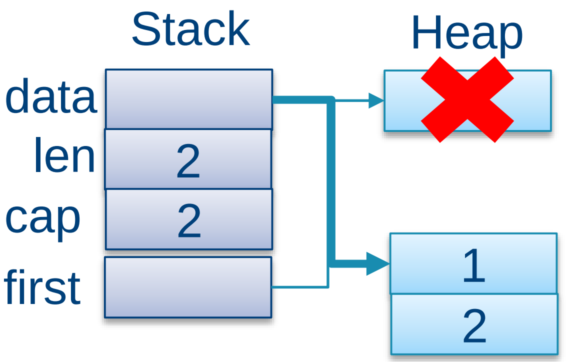
 }
```



Borrowing rules

- Rust supports borrowing:
  - Either: an arbitrary number of immutable references
  - Or: a single mutable reference
- To ensure safety, Rust ensures:
  - Modification through the owner is disallowed while borrows are outstanding
  - Lifetimes of borrowed references are always strictly included in the lifetime of the owner

Summary: Ownership and borrowing

- Together these concepts:
  - Can guarantee temporal memory safety statically
    - By ruling out simultaneous aliasing + mutation
  - Allow relatively flexible pointer manipulating programs
- Many advantages:
  - No need for a run-time (no garbage collection)
  - Also helps in avoiding data races (concurrency errors)
- Some disadvantages:
  - Non-trivial to use
  - Not as flexible as C

The Rust programming language

- Is one of the fastest growing languages at the moment
- The language has many other interesting features that we did not discuss
  - Pattern matching
  - Traits
  - Generics
  - …
- See:
  - https://www.rust-lang.org/

Overview

- Countermeasures of the future:
  - Protected module architectures
    - Fine grained isolation at machine code level
    - Supported in the most recent Intel Skylake processors under the name Intel Software Guard eXtentions (Intel SGX)
  - Safe systems programming languages
    - Compiled languages with low-level control over memory, but with strong safety assurance
    - Supported in the Rust programming language
  - Advanced compiler based countermeasures
    - Control-flow integrity (CFI)
    - Pointer-based checking

Control-flow integrity

- Most low-level attacks break the control flow as it is encoded in the source program
  - E.g. At the source code level, one always expects a function to return to its call site
- The idea of control-flow integrity is to instrument the code to check the "sanity" of the control-flow at runtime

Remember the heap-based buffer overflow

- Example vulnerable program:

```
typedef struct _vulnerable_struct
{
    char buff[MAX_LEN];
    int (*cmp)(char*,char*);
} vulnerable;

int is_file_foobar_using_heap( vulnerable* s, char* one, char* two )
{
    // must have strlen(one) + strlen(two) < MAX_LEN
    strcpy( s->buff, one );
    strcat( s->buff, two );
    return s->cmp( s->buff, "file://foobar" );
}
```

Example CFI at the source level

- The following code explicitly checks whether the cmp function pointer points to one of two known functions:

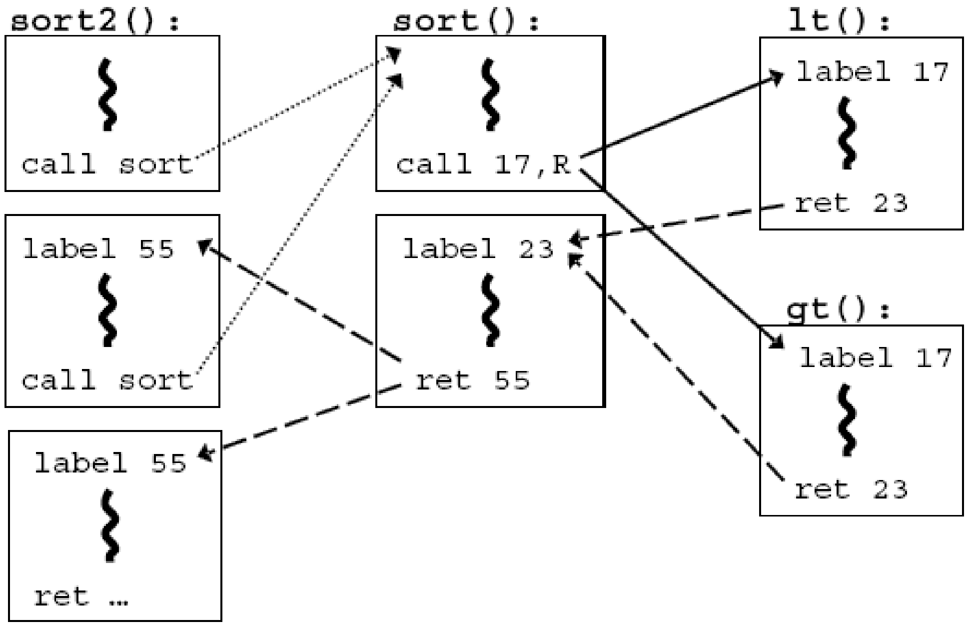
```
int is_file_foobar_using_heap( vulnerable* s, char* one, char* two )
{
    // ... elided code ...
    if( (s->cmp == strcmp) || (s->cmp == stricmp) ) {
        return s->cmp( s->buff, "file://foobar" );
    } else {
        return report_memory_corruption_error();
    }
}
```

General CFI

- In general, similar sanity checks can be done on any *computed control flow transfer*
  - Mainly: calls through function pointers, and returns
- The challenge is to do this
  - Efficiently
  - And precisely
- The original CFI determined a Control Flow Graph of the program, and then inserted *label-based checks*

Example CFI with labels

```
bool lt(int x, int y) {
    return x < y;
}
bool gt(int x, int y) {
    return x > y;
}
sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
    sort( b, len, gt );
}
```



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  - Safe systems programming languages
    - Compiled languages with low-level control over memory, but with strong safety assurance
    - Supported in the Rust programming language
  - Advanced compiler based countermeasures
    - Control-flow integrity (CFI)
    - ➡ Pointer-based checking

Pointer-based checking for C

- Challenging, because:
  - For compatibility reasons, you should not change the size of a pointer (so no **fat** pointers)
  - Performance overhead should be low
- The most promising approach uses metadata about pointers maintained in a disjoint metadata space
- For a detailed discussion, see:
  - Santosh Nagarakatte, Milo M. K. Martin, Steve Zdancewic: Everything You Want to Know About Pointer-Based Checking. SNAPL 2015

How does it work?

- For each pointer (i.e. each memory address), we maintain **metadata** at run-time in a separate area of memory, e.g.:
  - **Base** and **bound** information: what is the size of the memory blob that this pointer is valid for?
  - **Lock** and **key** information to detect temporal safety issues
- Intel Memory Protection Extensions (Intel MPX) provides hardware support for maintaining such metadata
  - Currently only base and bound

(a) Memory Allocations

```
p = malloc(size);
```

```
p_key = next_key++;
p_lock = allocate_lock();
*(p_lock) = p_key;
p_ base = p;
p_bound = p != 0 ? p+size: 0;
```

(b) Memory Deallocations

```
free(p);
```

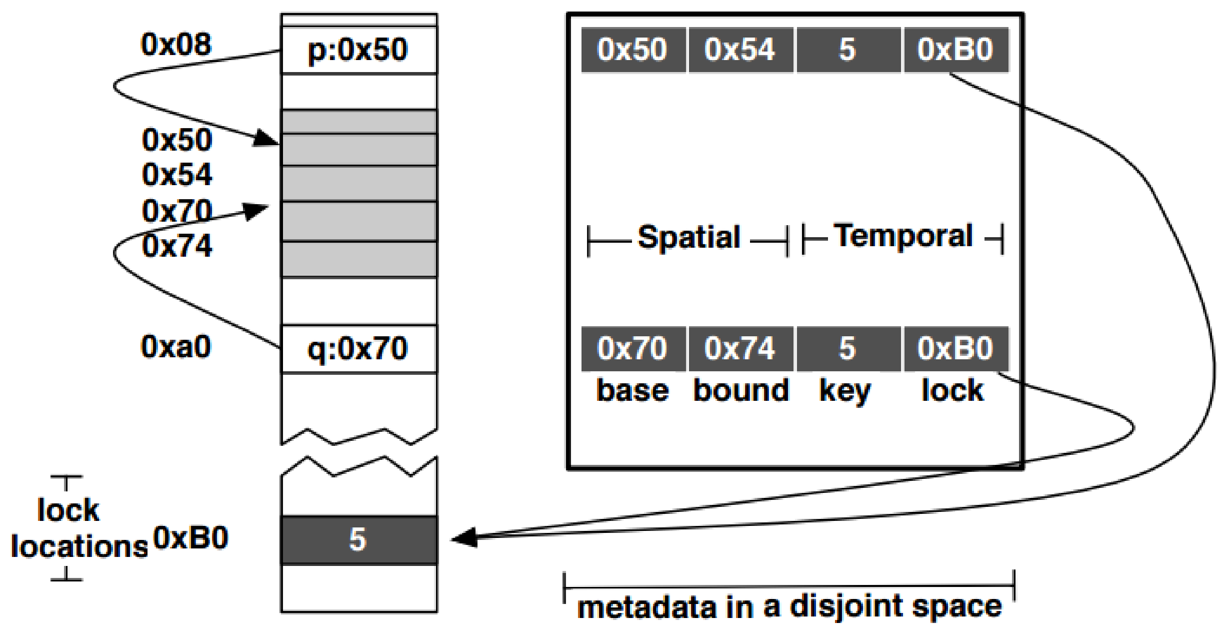
```
*(p_lock) = INVALID;
deallocate_lock(p_lock);
```

(c) Temporal Check

```
tcheck(p_key, p_lock) {
  if (p_key != *(p_lock))
    raise exception();
}
```

(d) Spatial Check

```
scheck(p, p_base, p_bound, size) {
  if (p < p_base ||
      p + size >= p_bound)
    raise exception();
}
```



Performance costs

- Software-only implementations:
  - From a few percent up to 250% execution time overhead
- Hardware-supported implementations:
  - Approximately 20% execution time overhead

Conclusions

- Vulnerabilities in infrastructural systems software (operating systems, servers, middleware) have been an important concern for security for decades
- Memory safety related vulnerabilities are one of the most important categories of vulnerabilities in systems software
- Decades of research are resulting in some interesting new approaches to:
  - Protect application modules from infrastructural software
  - Prevent memory safety vulnerabilities through safe systems programming language
  - Comprehensively detect triggering of memory safety vulnerabilities at run-time for C with reasonable performance
- If you are interested in following these developments more closely, come talk to me about possible collaborations!

References

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- U. Erlingsson, Y. Younan, F. Piessens, Low-level software security by example, Handbook of Information and Communication Security, 2010
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