程序的机器级表示：过程

Machine-Level Programming : Procedures

本章内容

Topic

- 栈的结构

  Stack Structure

- 过程调用规范

  Calling Conventions

- 递归

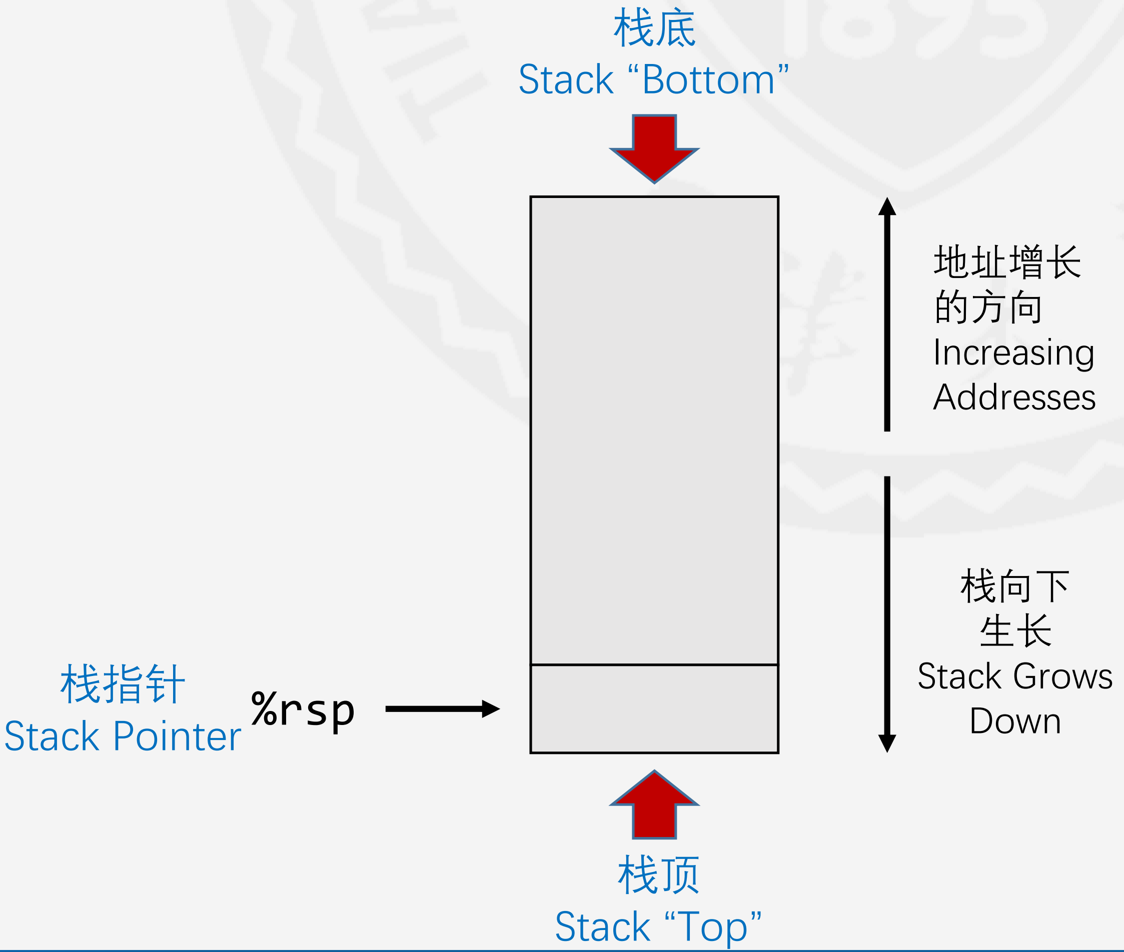
  Recursion

栈的结构

Stack Structure

x86-64的栈
x86-64 Stack

- 使用栈的规则管理内存区域
  Region of memory managed with stack discipline
- 向低地址方向生长
  Grows toward lower addresses
- 寄存器 `%rsp` 栈的最低地址
  Register `%rsp` contains lowest stack address

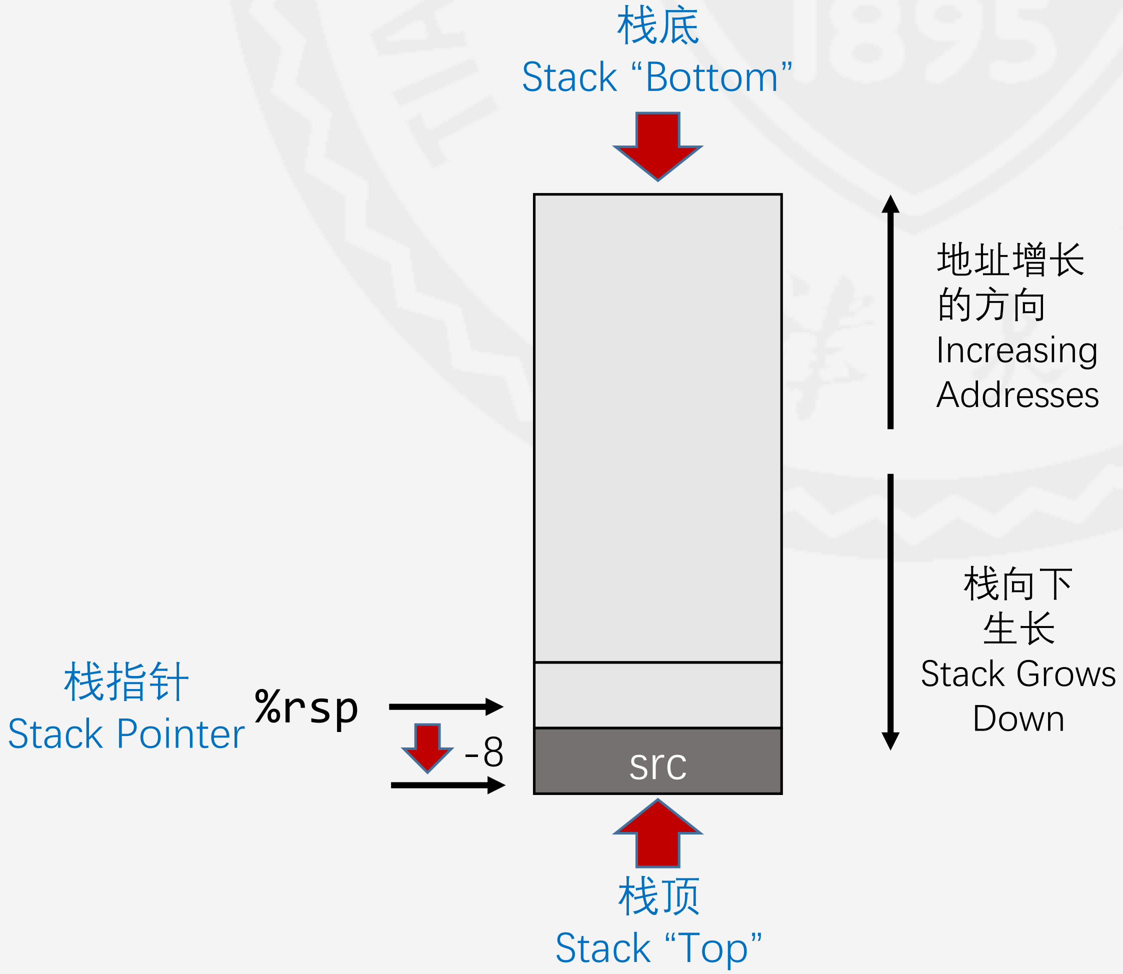


栈的结构

Stack Structure

x86-64的栈：入栈
x86-64 Stack: Push

- `pushq src`
  1. 从 `src` 中取出操作数
     Fetch operand at `src`
  2. `%rsp` 减 8
     Decrement `%rsp` by 8
  3. 将操作数的值写入`%rsp`指向的地址
     Write operand at address given by `%rsp`

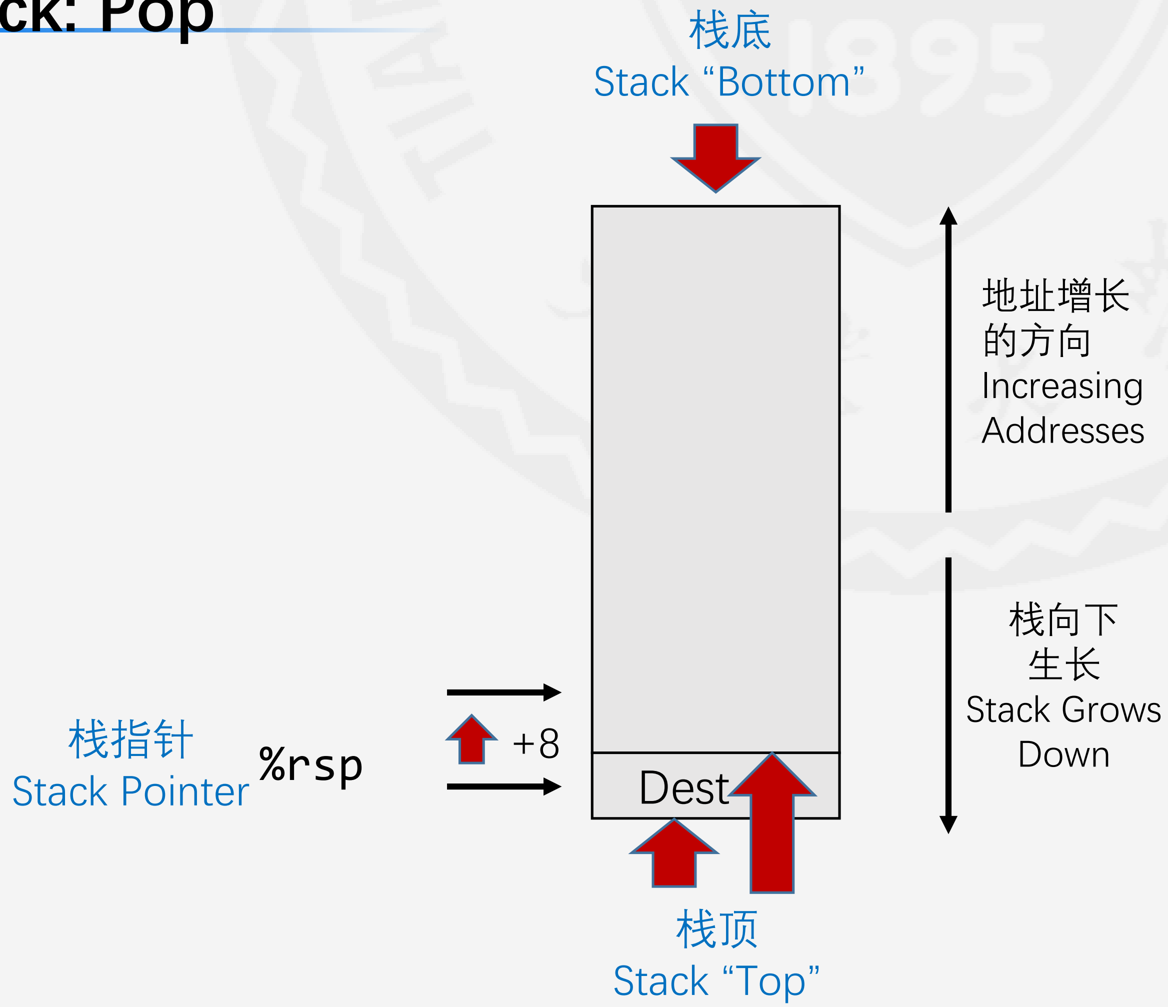


栈的结构

Stack Structure

x86-64的栈：出栈
x86-64 Stack: Pop

- `popq dest`
  1. 从 `%rsp` 指向的地址中取出值
     Fetch value in `%rsp`
  2. 将值写入 `dest`
     Write value to operand `dest`
  3. `%rsp` 加 8
     Increment %rsp by 8



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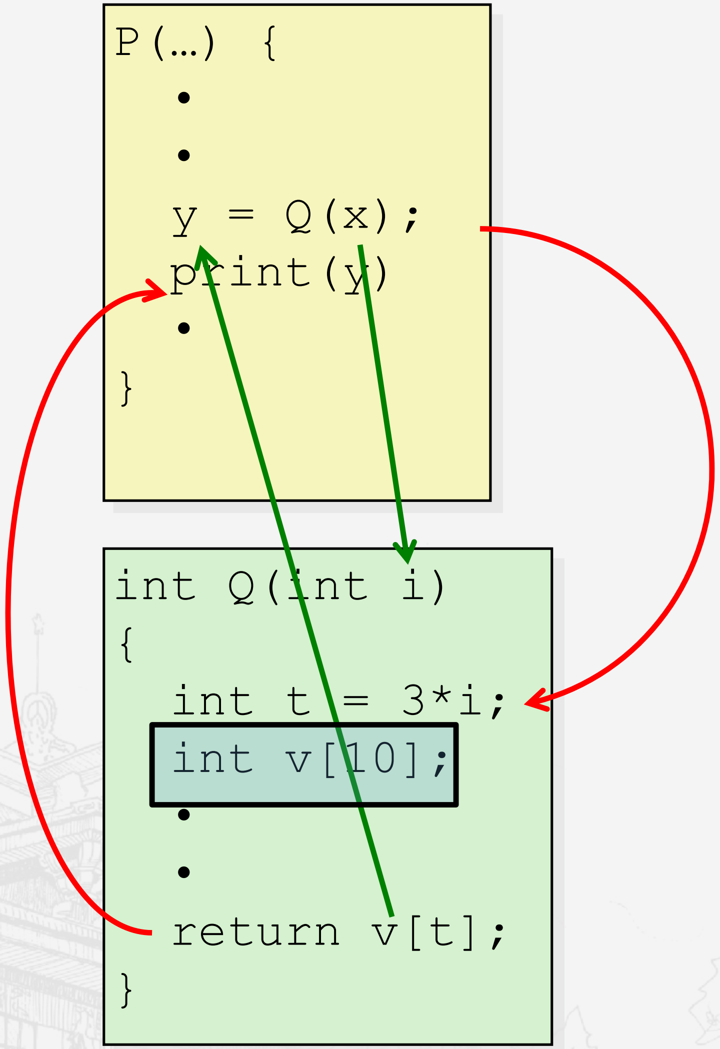
过程调用规范

Calling Conventions



- 控制流转移
  Passing control flow
  - 跳转至过程代码的开始位置（过程调用时）
    To beginning of procedure code
  - 跳转至返回点（过程返回时）
    Back to return point
- 数据传递
  Passing data
  - 过程的参数
    Procedure arguments
  - 返回值
    Return value
- 存储管理
  Memory management
  - 在过程执行时分配存储空间
    Allocate during procedure execution
  - 在过程返回时回收空间
    Deallocate upon return
- 所有过程调用的都是通过机器指令实现的（软件实现而非硬件实现）
  Mechanisms all implemented with machine instructions
- x86-64在实现某个过程时，只选择实现当前过程所需要的机制
  x86-64 implementation of a procedure uses only those mechanisms required

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    Passing Control Flow
  - 数据传递
    Passing Data
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过程调用规范

Passing Control

过程控制流
Procedure Control Flow

- 使用栈支持过程的调用和返回
  Use stack to support procedure call and return
- **过程调用：** `call label`
  Procedure call: `call label`
  - 将返回地址压入栈
    Push return address on stack
  - 跳转至 `label` 标签
    Jump to `label`
- 返回地址
  Return address:
  - 紧接call指令的指令所在地址
    Address of the next instruction right after call

- **过程返回：** `ret`
  Procedure return: `ret`
  - 从栈中弹出返回地址
    Pop address from stack
  - 跳转至返回地址
    Jump to address

举例：控制流转移
Passing Control Flow Examples

```
void multstore
     (long x, long y, long *dest)
{
    long t = mult2(x, y);
    *dest = t;
}
```

```
0000000000400540 <multstore>:
  400540: push   %rbx              # Save %rbx
  400541: mov    %rdx,%rbx         # Save dest
  400544: callq  400550 <mult2>    # mult2(x,y)
  400549: mov    %rax,(%rbx)       # Save at dest
  40054c: pop    %rbx              # Restore %rbx
  40054d: retq                     # Return
```

```
long mult2 (long a, long b)
{
  long s = a * b;
  return s;
}
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax    # a
  400553:  imul   %rsi,%rax    # a * b
  400557:  retq                # Return
```

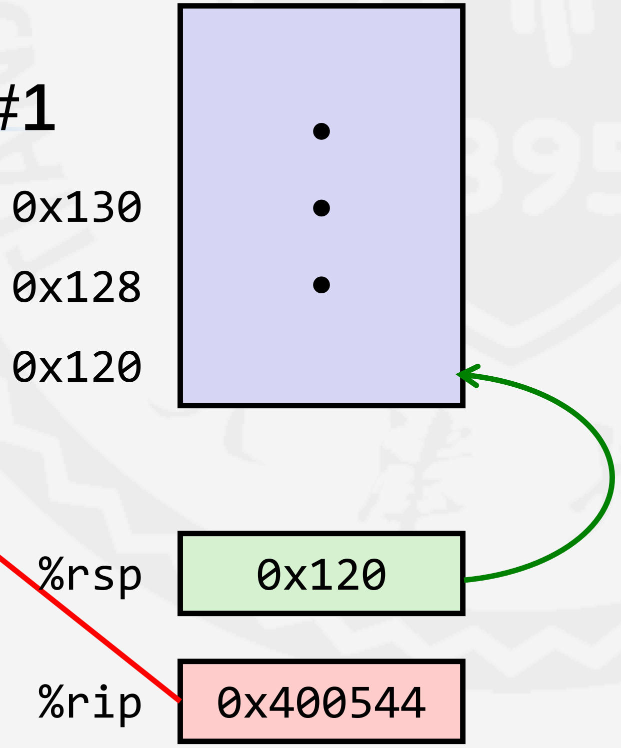
过程调用规范

Passing Control

举例：控制流转移 #1
Passing Control Flow Examples #1

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



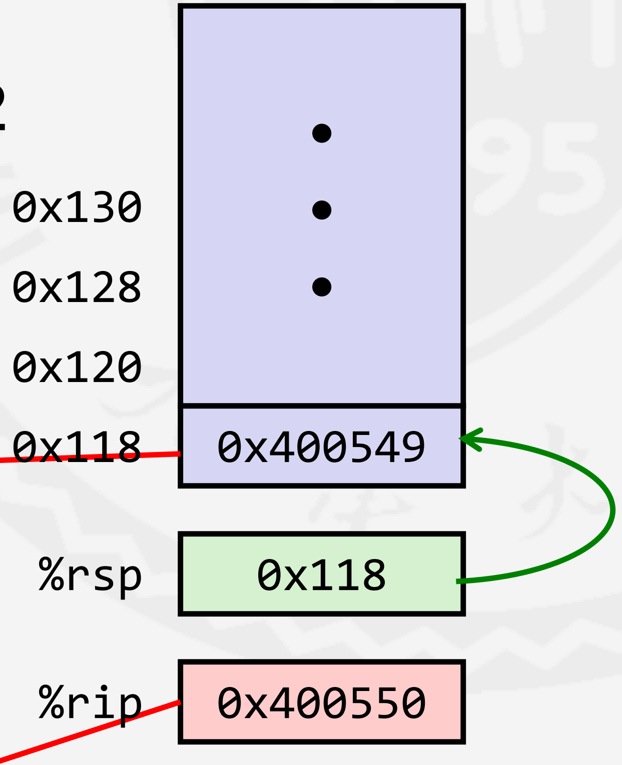
过程调用规范

Passing Control

举例：控制流转移 #2
Passing Control Flow Examples #2

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



过程调用规范

Passing Control

举例：控制流转移 #3
Passing Control Flow Examples #3

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```

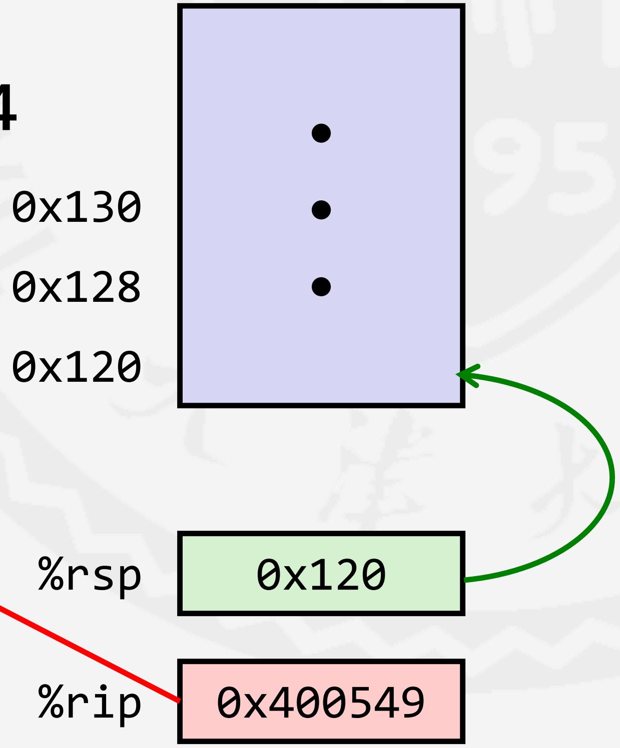
0x130	•
0x128	•
0x120	•
0x118	0x400549

%rsp	0x118
%rip	0x400557

举例：控制流转移 #4
Passing Control Flow Examples #4

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



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    Passing Data

  - 存储管理

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过程调用规范

Passing Control

过程数据流
Procedure Data Flow

- 前6个参数通过寄存器传递

  First 6 arguments passed by registers

%rdi
%rsi
%rdx
%rcx
%r8
%r9

- 返回值

  Return value

%rax

- 剩余参数通过栈传递
- Other arguments passed by Stack

• • •
Arg *n*
• • •
Arg 8
Arg 7

- 只有需要的时候栈才会分配空间

  Only allocate stack space when needed

举例：过程数据流
Data Flow Example

```
void multstore
    (long x, long y, long *dest)
{
    long t = mult2(x, y);
    *dest = t;
}
```

```
0000000000400540 <multstore>:
  # x in %rdi, y in %rsi, dest in %rdx
  • • •
  400541: mov    %rdx,%rbx        # Save dest
  400544: callq  400550 <mult2>   # mult2(x,y)
  # t in %rax
  400549: mov    %rax,(%rbx)      # Save at dest
  • • •
```

```
long mult2 (long a, long b)
{
    long s = a * b;
    return s;
}
```

```
0000000000400550 <mult2>:
  # a in %rdi, b in %rsi
  400550:  mov    %rdi,%rax   # a
  400553:  imul   %rsi,%rax   # a * b
  # s in %rax
  400557:  retq               # Return
```

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过程调用规范

Passing Control

基于栈的程序设计语言
Stack-Based Languages

- 支持递归的编程语言
  Languages that support recursion
  - e.g., C, Pascal, Java ,C#
  - 代码必须是可重入的
    Code must be “Reentrant”
    - 一个过程可以有多个实例
      Multiple simultaneous instantiations of single procedure
  - 需要空间存储每个过程实例的状态
    Need some place to store state of each instantiation
    - 参数
      Arguments
    - 局部变量
      Local variables
    - 返回地址
      Return address

- 栈的规则
  Stack discipline
  - 每个过程的状态只需要保存有限的时间
    State for given procedure needed for limited time
  - 从调用开始至返回结束
    From when called to when return
  - 被调用者先于调用者返回
    Callee returns before caller does
- 栈空间以**帧**的方式进行分配
  Stack allocated in **Frames**
  - 存储每个过程实例的状态
    state for single procedure instantiation

过程调用规范

Passing Control

举例：调用链
Call Chain Example

```
yoo(…)
{
    .
    .
    who();
    .
    .
}
```

```
who(…)
{
    ...
    amI();
    ...
    amI();
    ...
}
```

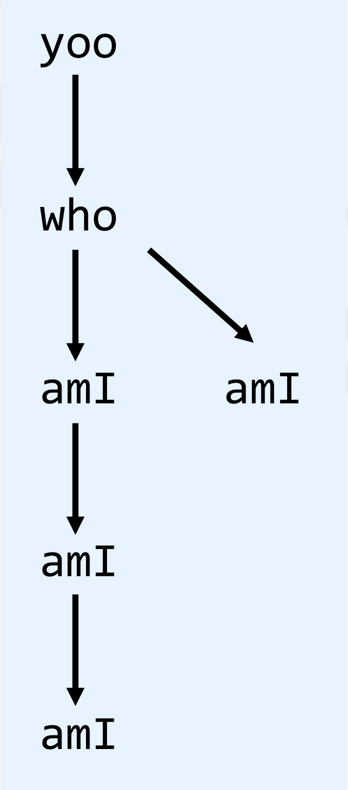
```
amI(…)
{
    .
    .
    amI();
    .
    .
}
```

amI() 是递归的

Procedure `amI()` is recursive

调用链示意

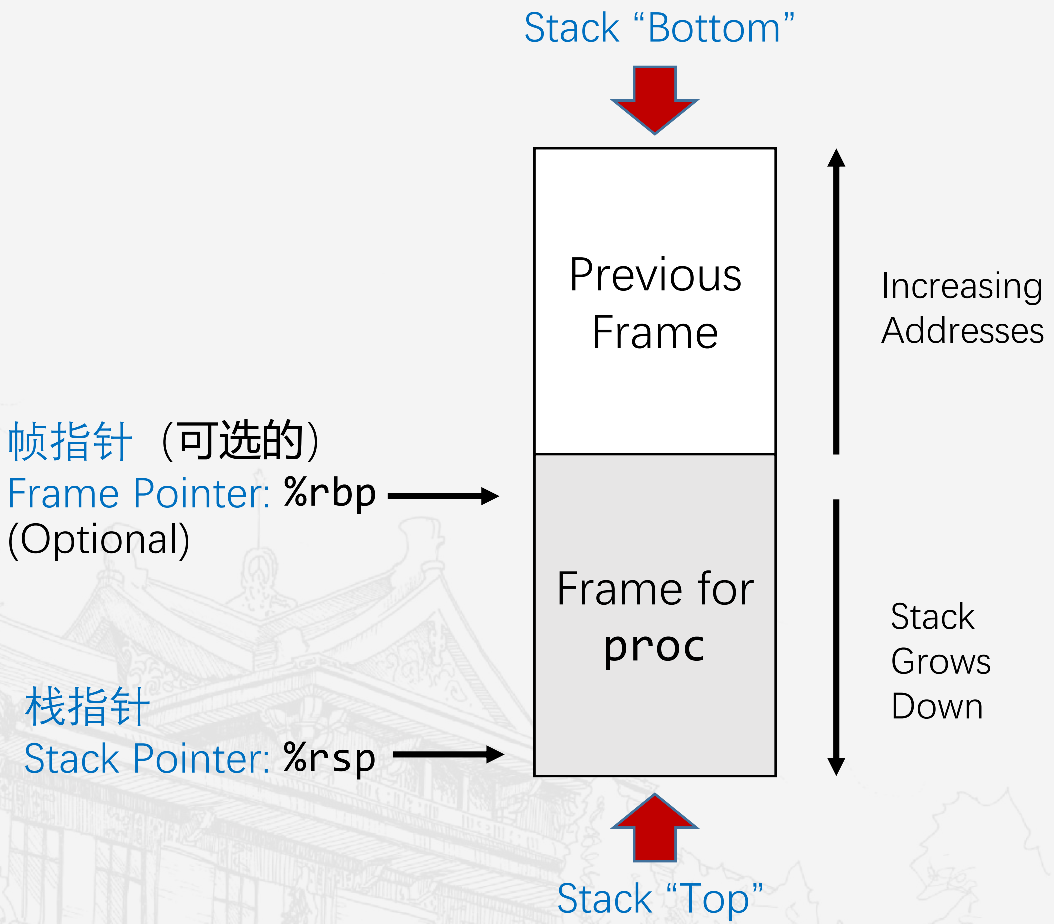
Call Chain



过程调用规范

Passing Control

栈帧
Stack Frames



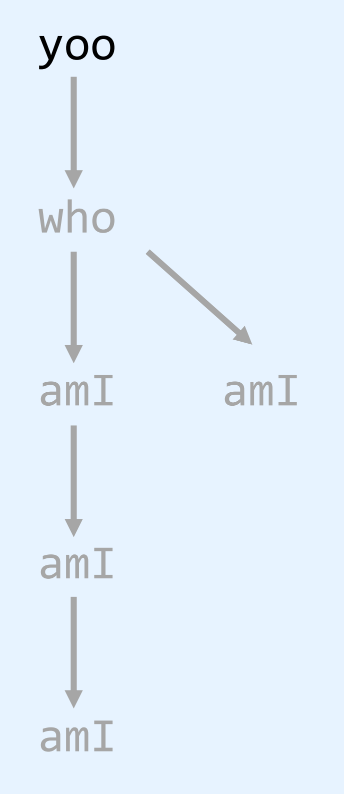
- 内容
  Contents
  - 返回地址
    Return address
  - 局部变量 （如果需要）
    Local variables (if needed)
  - 参数（如果需要）
    Other Arguments (if needed)
  - 其他临时空间（如果需要）
    Temporary space (if needed)
- 管理
  Management
  - 进入过程后，分配栈帧空间
    Space allocated when enter procedure
    - “建立”代码
      “Set-up” code
    - 包括 call指令中的入栈操作
      Includes push by call instruction
  - 过程返回前，释放栈帧空间
    Deallocated when return
    - “结束”代码
      “Finish” code
    - 包括 ret 指令中的出栈操作
      Includes pop by ret instruction

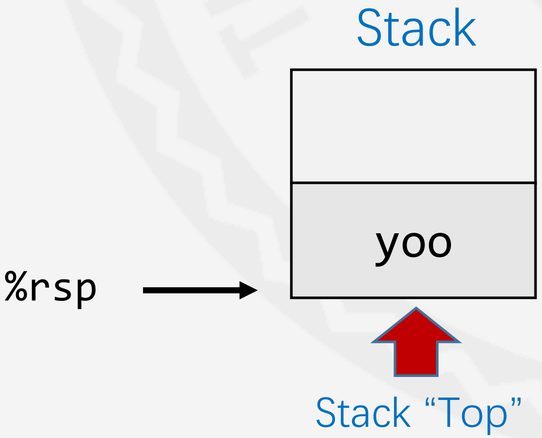
过程调用规范

Passing Control

举例：调用链
Call Chain Example

```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```





过程调用规范

Passing Control

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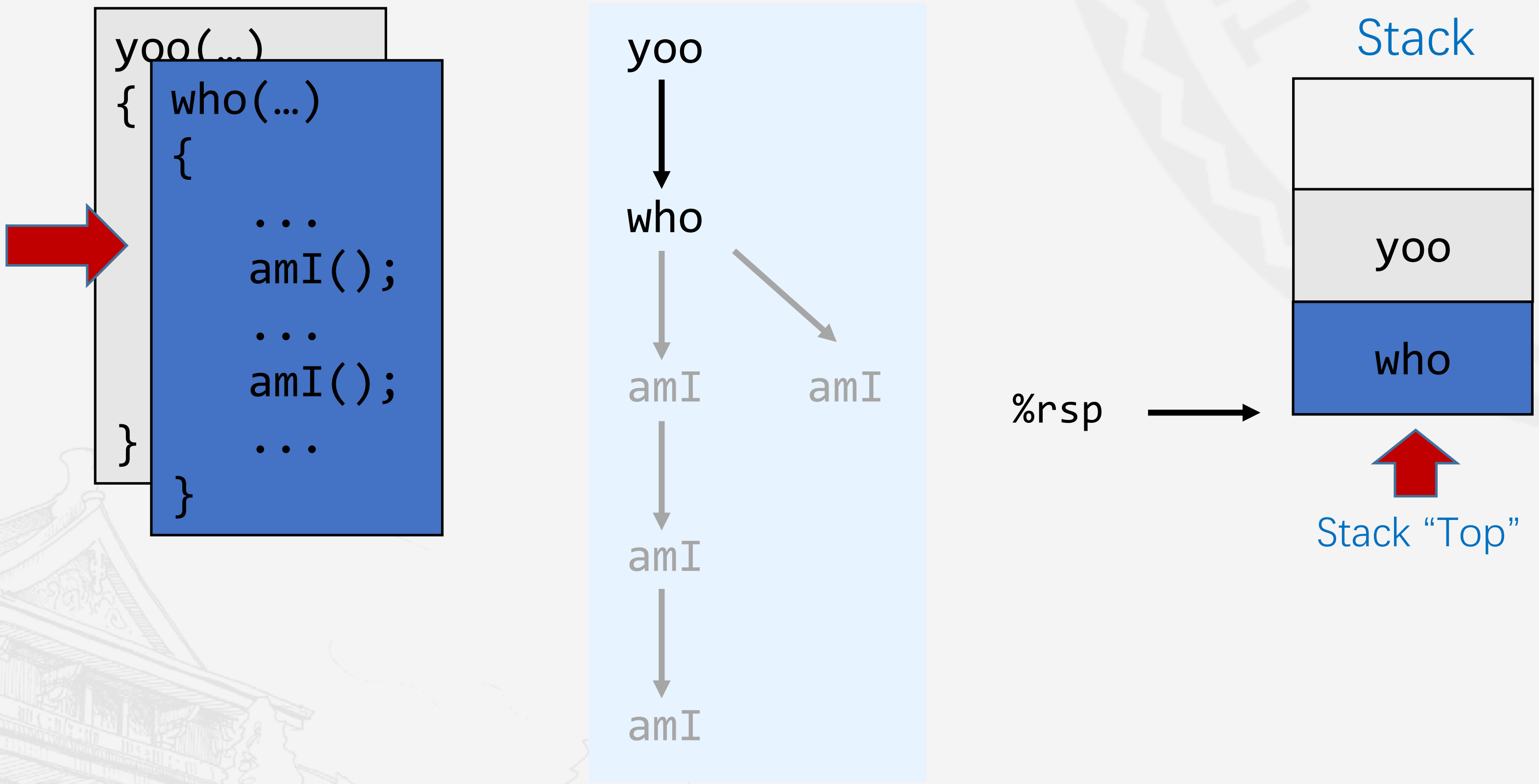
Call Chain Example



过程调用规范

Passing Control

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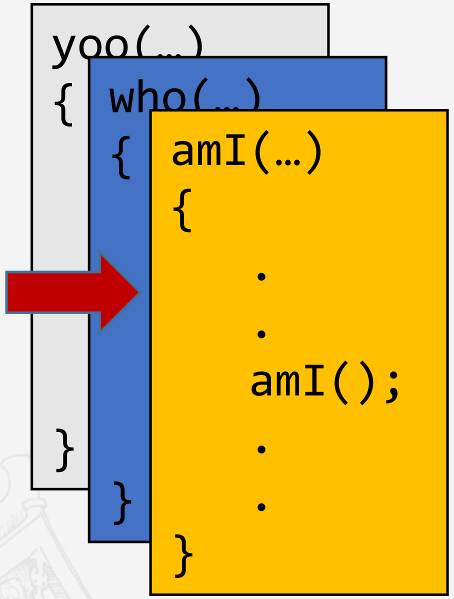
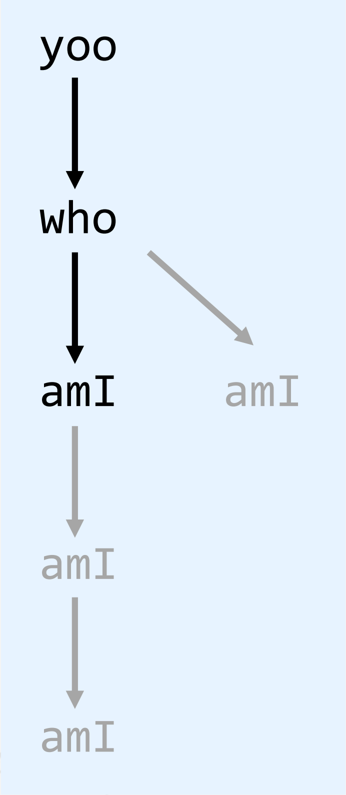
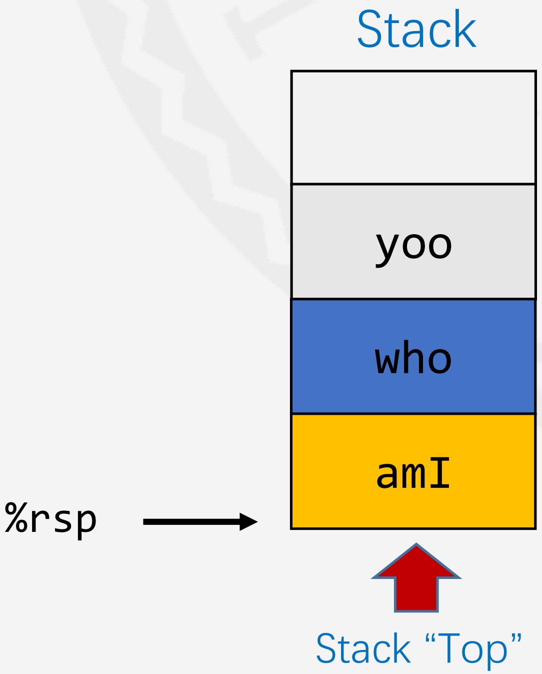
Call Chain Example







过程调用规范

Passing Control

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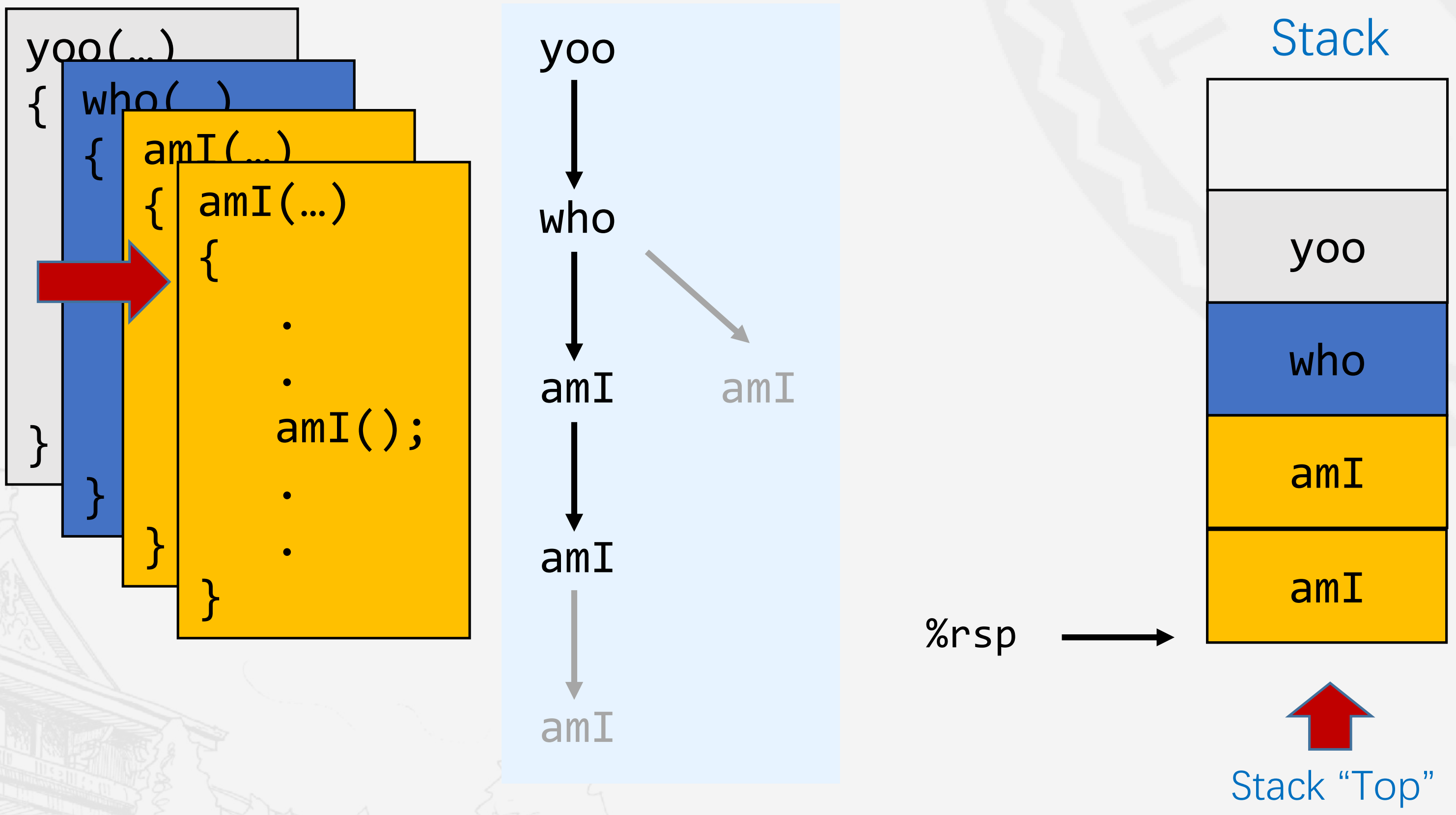

过程调用规范

Passing Control

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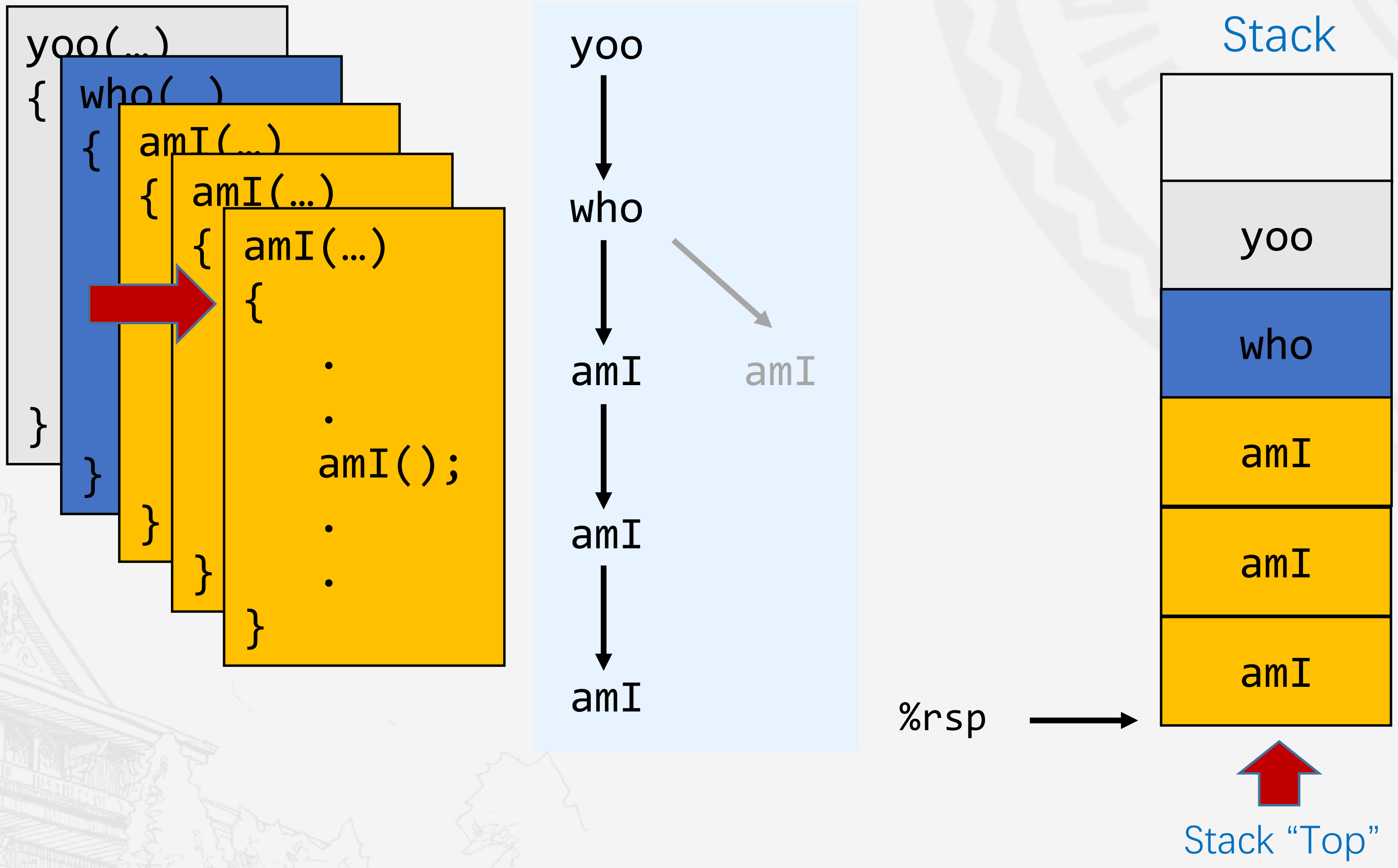
Call Chain Example



过程调用规范

Passing Control

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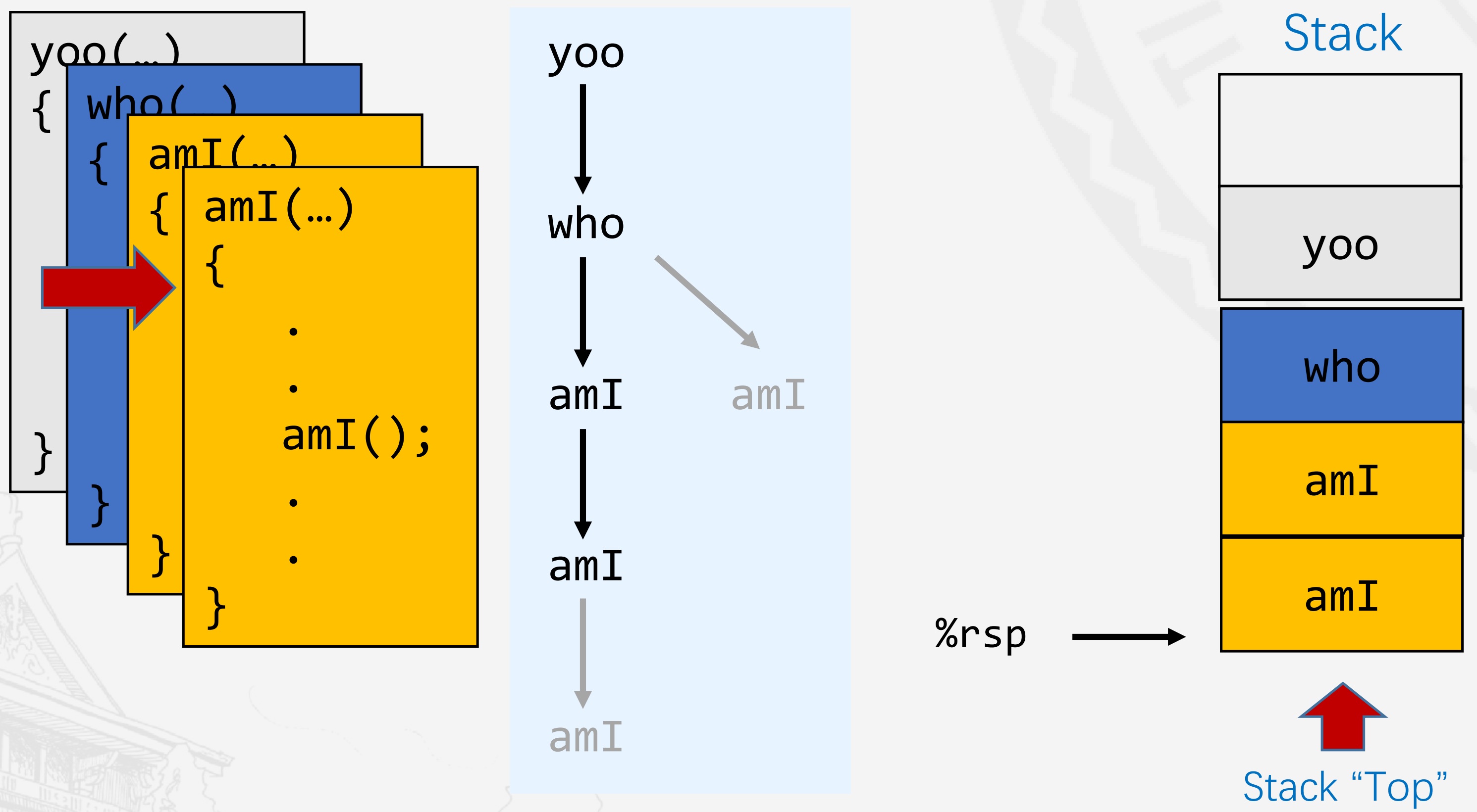
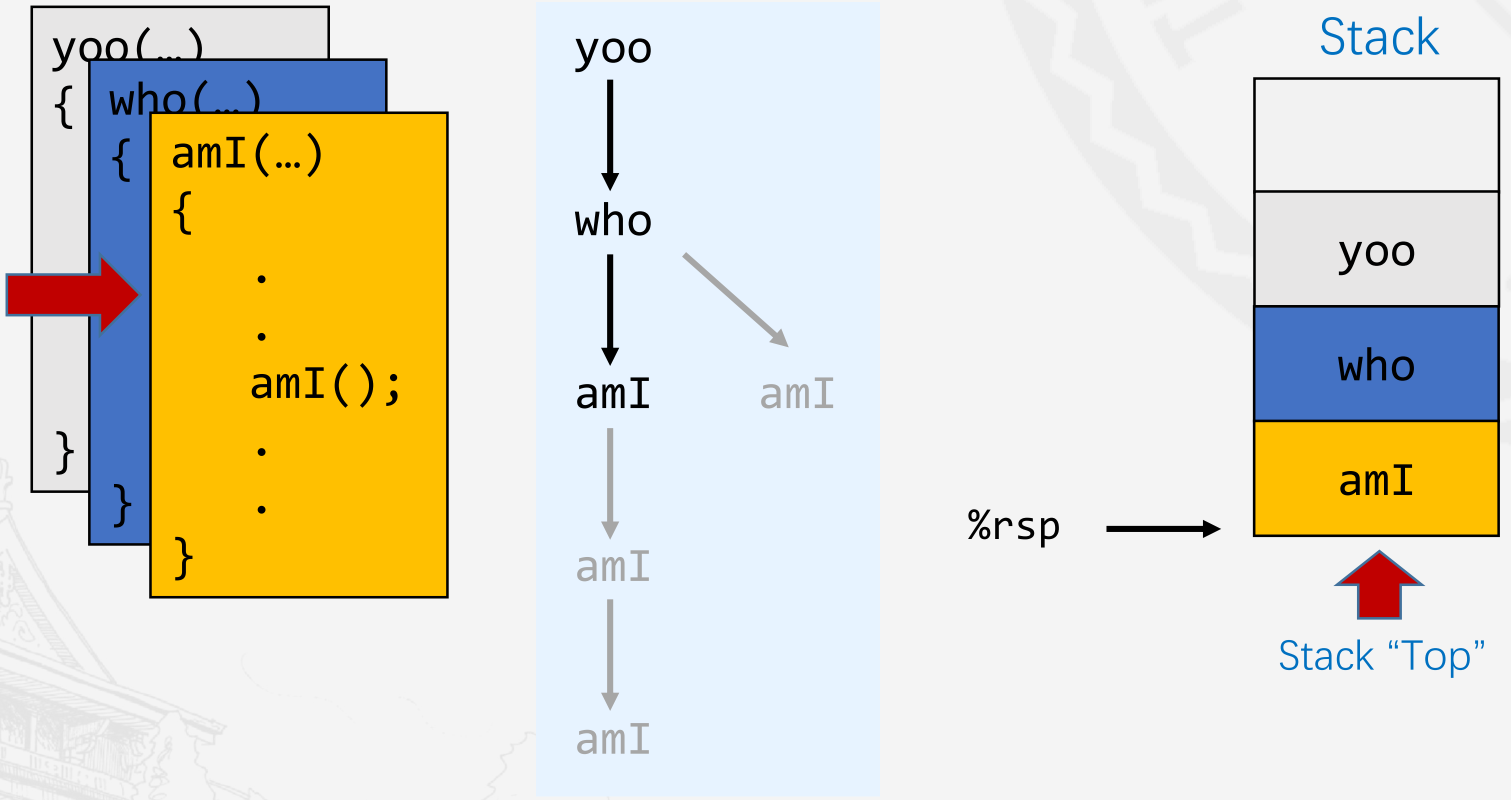


过程调用规范

Passing Control

举例：调用链
Call Chain Example



过程调用规范

Passing Control

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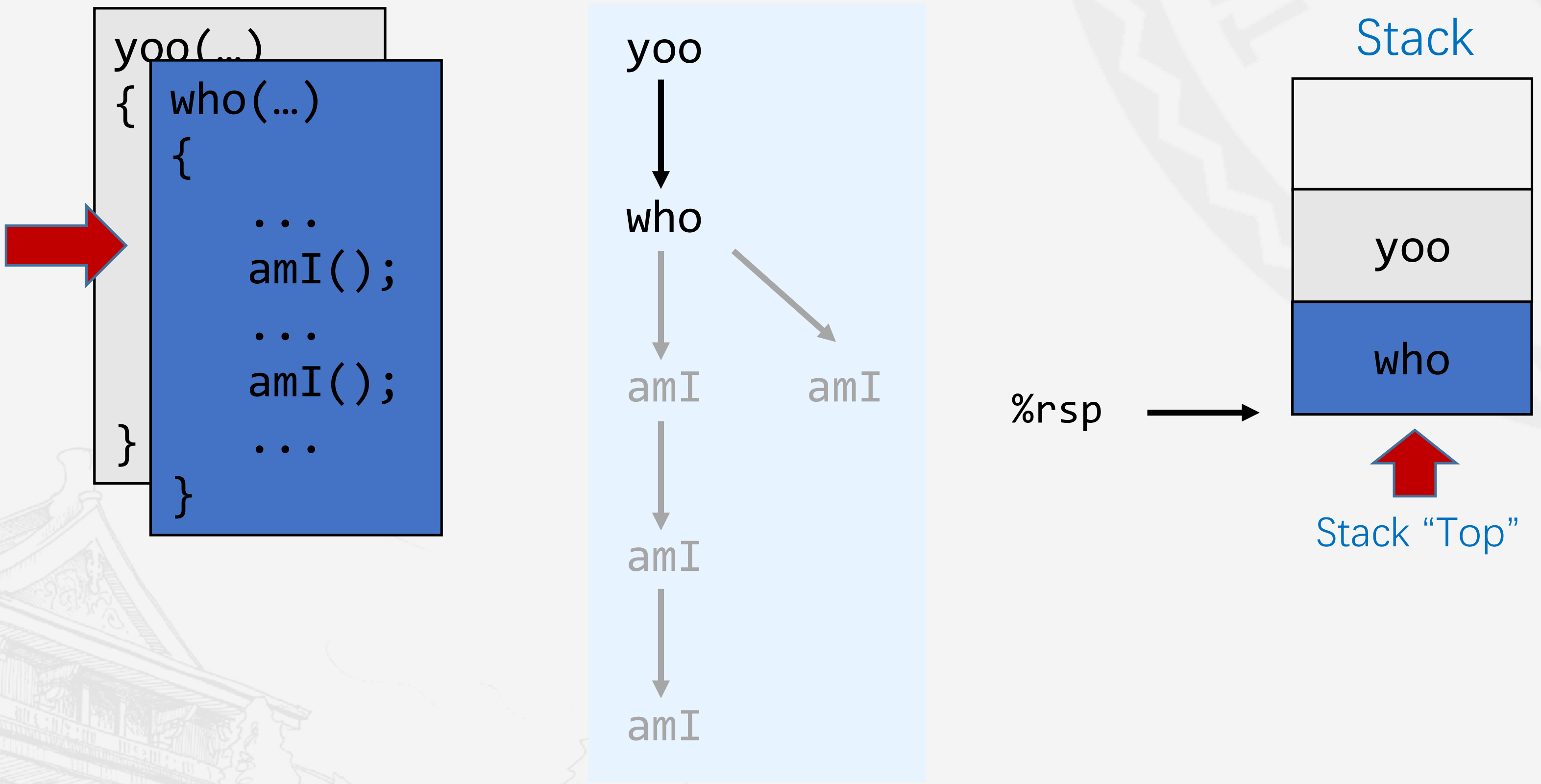
Call Chain Example



过程调用规范

Passing Control

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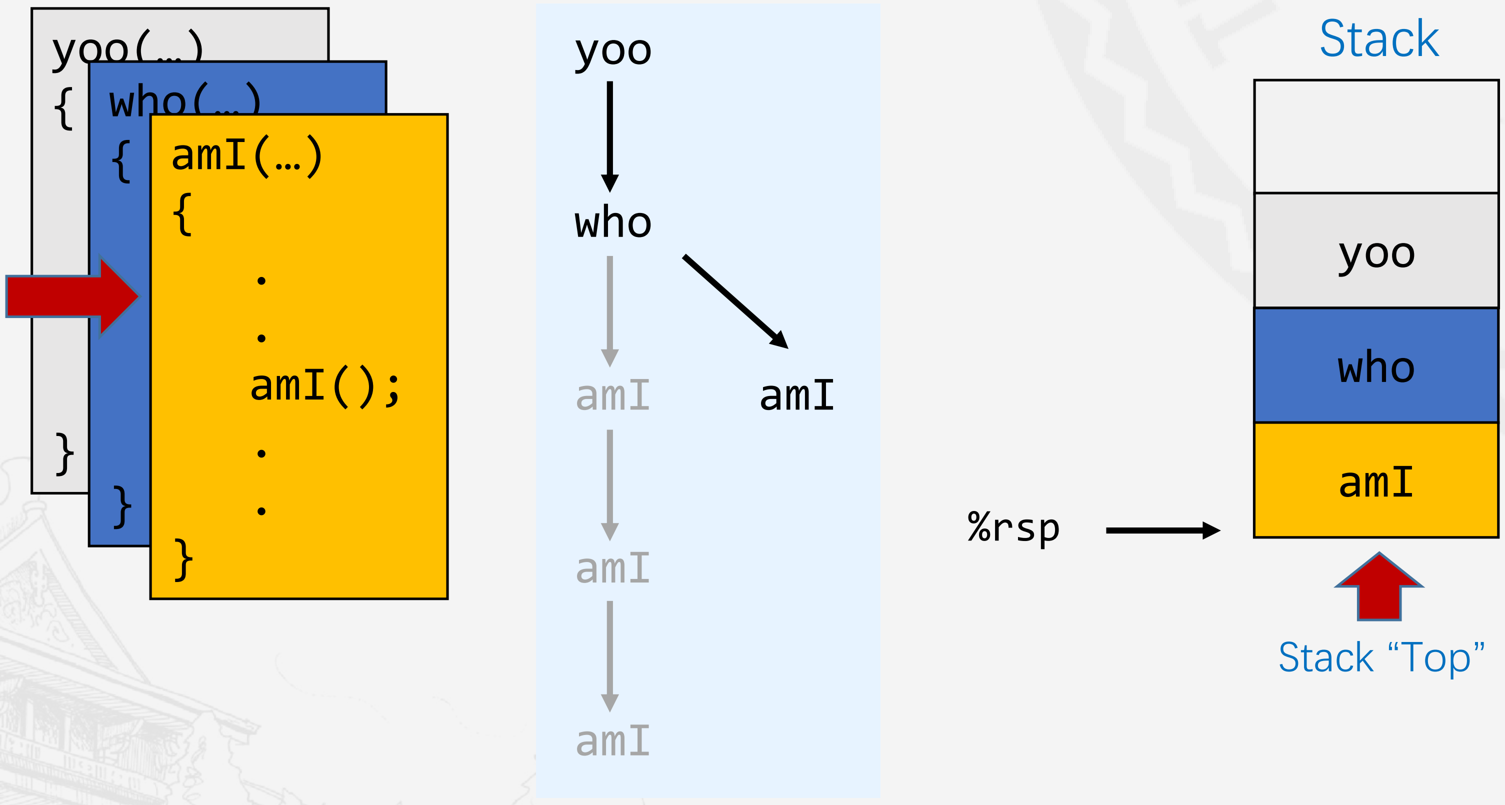
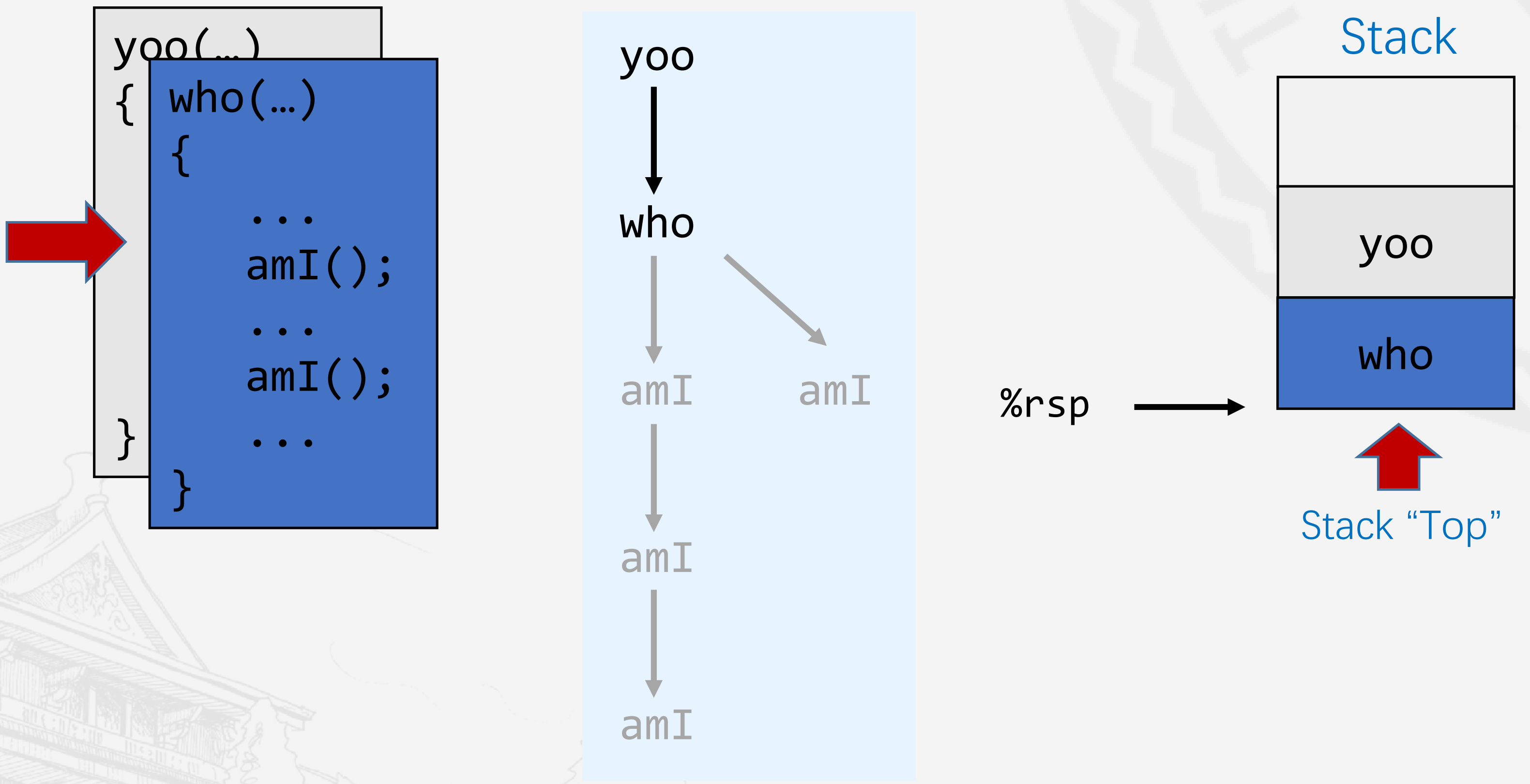


举例：调用链
Call Chain Example

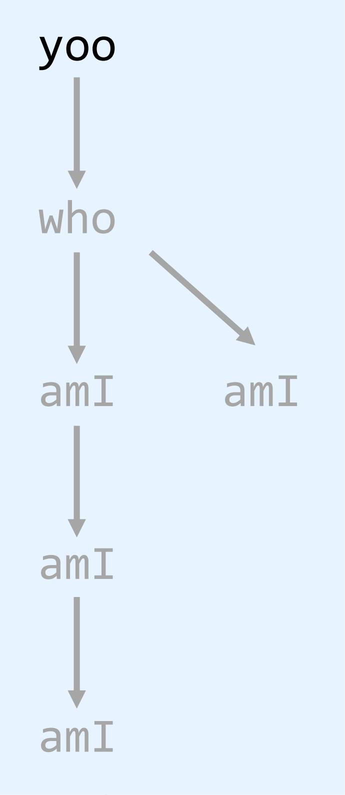


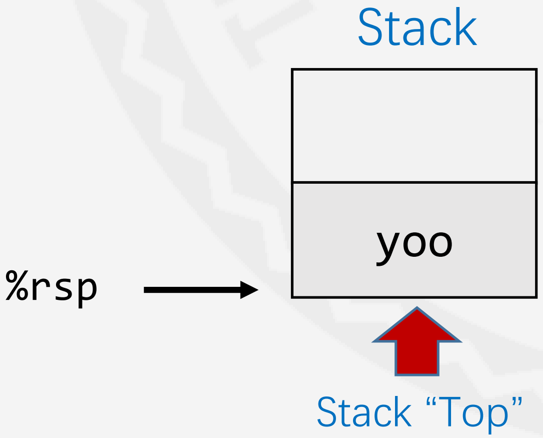
过程调用规范

Passing Control

举例：调用链
Call Chain Example

```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```



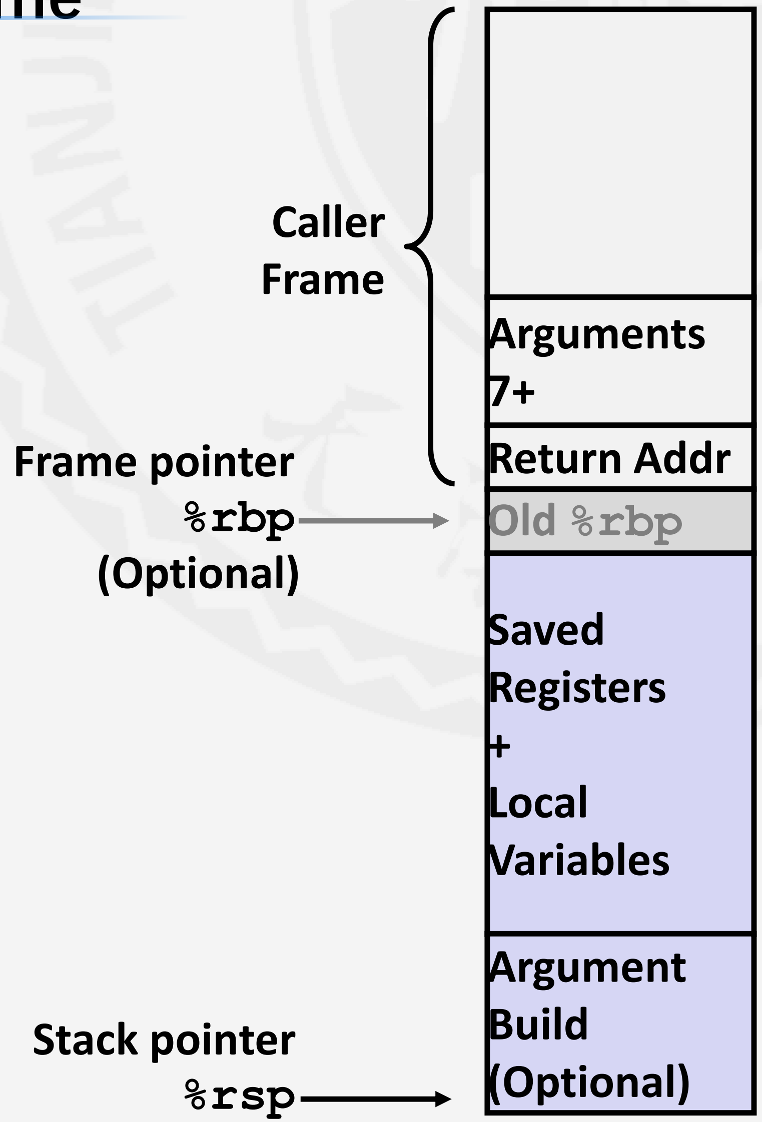


过程调用规范

Passing Control

x86-64/Linux 栈帧
x86-64/Linux Stack Frame

- 当前栈帧（从顶至底）
  Contents
  - 参数：即将要调用的函数的参数
    “Argument build:” Parameters for function about to call
  - 本地变量：在寄存器中保存不下的
    Local variables：If can’t keep in registers
  - 保存的寄存器上下文信息
    Saved register context
  - 指向调用者的栈帧底部的指针 （可选）
    Old frame pointer (optional)
- 调用者栈帧
  Caller Stack Frame
  - 返回地址
    Return address
    - 调用call指令时入栈
      Pushed by call instruction
  - 本次调用的参数
    Arguments for this call



过程调用规范

Passing Control

举例：incr 过程
Example: incr

```
long incr(long *p, long val)
{
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

```
incr:
  movq    (%rdi), %rax
  addq    %rax, %rsi
  movq    %rsi, (%rdi)
  ret
```

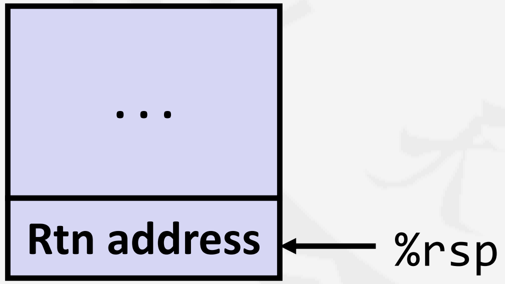
Register	Use(s)
%rdi	Argument **p**
%rsi	Argument **val**, **y**
%rax	**x**, Return value

举例：调用 incr #1
Example: Calling incr #1

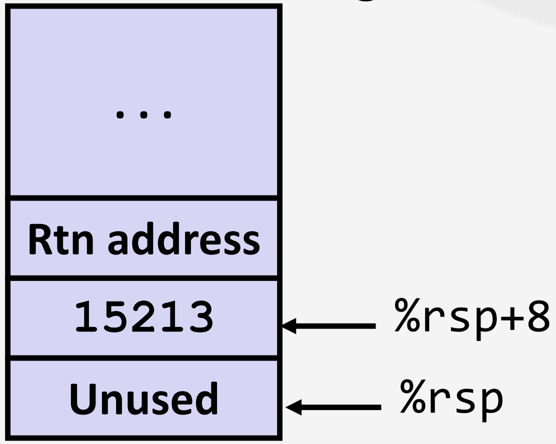
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

栈的初始结构
Initial Stack Structure



指令执行后的栈的结构
Resulting Stack Structure



过程调用规范

Passing Control

举例：调用 incr #2
Example: Calling incr #2

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure

...	
Rtn address	
15213	← %rsp+8
Unused	← %rsp

Register	Use(s)
%rdi	&v1
%rsi	3000

过程调用规范

Passing Control

举例：调用 incr #3
Example: Calling incr #3

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure

Stack	
...	
Rtn address	
18213	← %rsp+8
Unused	← %rsp

Register	Use(s)
%rdi	&v1
%rsi	3000

过程调用规范

Passing Control

举例：调用 incr #4
Example: Calling incr #4

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure

...	
Rtn address	
18213	← %rsp+8
Unused	← %rsp

Register	Use(s)
%rax	Return value

更新后栈的结构

Updated Stack Structure

...	
Rtn address	← %rsp

过程调用规范

Passing Control

举例：调用 incr #5
Example: Calling incr #5

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

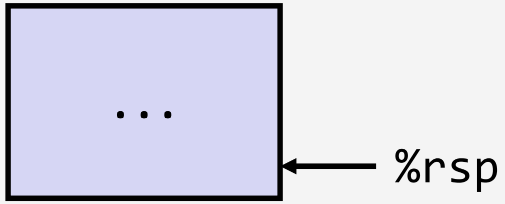
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Updated Stack Structure

Register	Use(s)
%rax	Return value

栈的最终结构

Final Stack Structure



寄存器使用惯例
Register Saving Conventions

- 寄存器可以用做临时存储吗?
  Can register be used for temporary storage?

```
yoo:
    • • •
    movq $15213, %rdx
    call who
    addq %rdx, %rax
    • • •
    ret
```

```
who:
    • • •
    subq $18213, %rdx
    • • •
    ret
```

- %rdx 的内容会被 who 覆盖
  Contents of register %rdx overwritten by who
- 这会引发逻辑错误 ➙ 需要做点什么
  This could be trouble ➙ something should be done!
  - 建立一种使用寄存器的协调机制
    Need some coordination

过程调用规范

Passing Control

寄存器使用惯例
Register Saving Conventions

- 当 yoo 调用 who:
  When procedure yoo calls who:
  - yoo是调用者
    yoo is the caller
  - Who是被调用者
    who is the callee

- **“调用者保护”**
  “Caller Saved”
  - 在调用前，调用者把临时数据保存到自己的栈帧中
    Caller saves temporary values in its frame before the call
- **“被调用者保护”**
  “Callee Saved”
  - 被调用者在使用寄存器前将降临时数据保存至自己的栈帧中
    Callee saves temporary values in its frame before using
  - 在被调用者返回前恢复这些数据
    Callee restores them before returning to caller

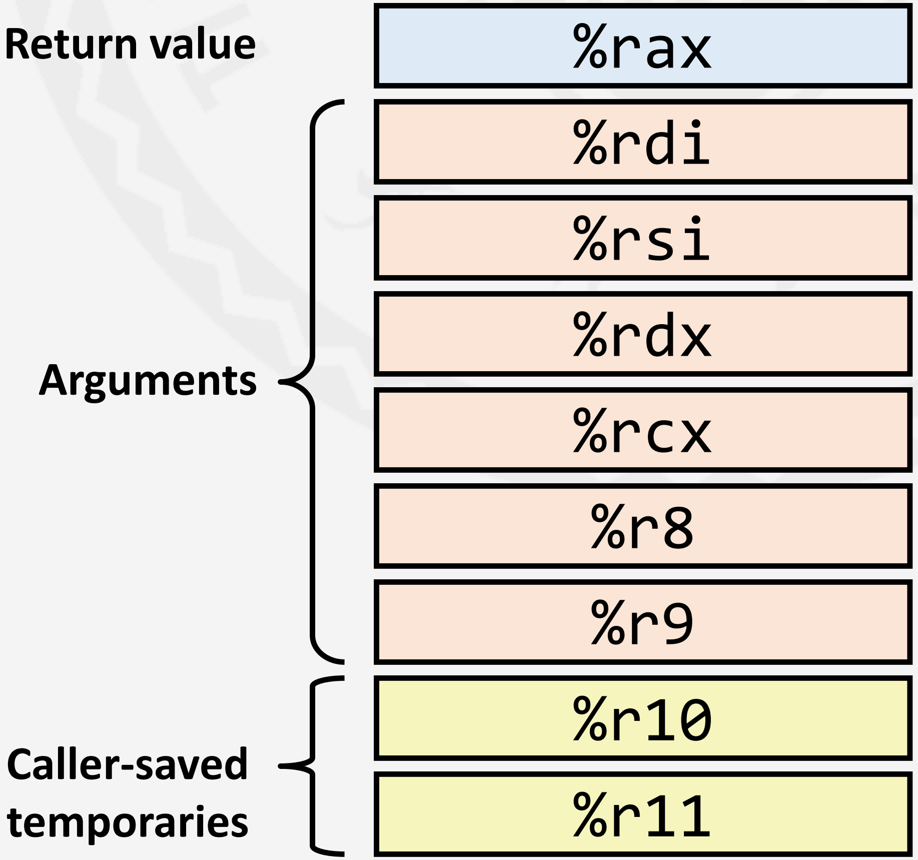
过程调用规范

Passing Control

x86-64 Linux 中寄存器的用途 #1
x86-64 Linux Register Usage #1

- %rax, %rdi, %rsi, %rdx, %rcx, %r8, %r9, %r10, %r11
  - 调用者保护
    Caller-saved
  - 在过程中值可能被修改
    Can be modified by procedure

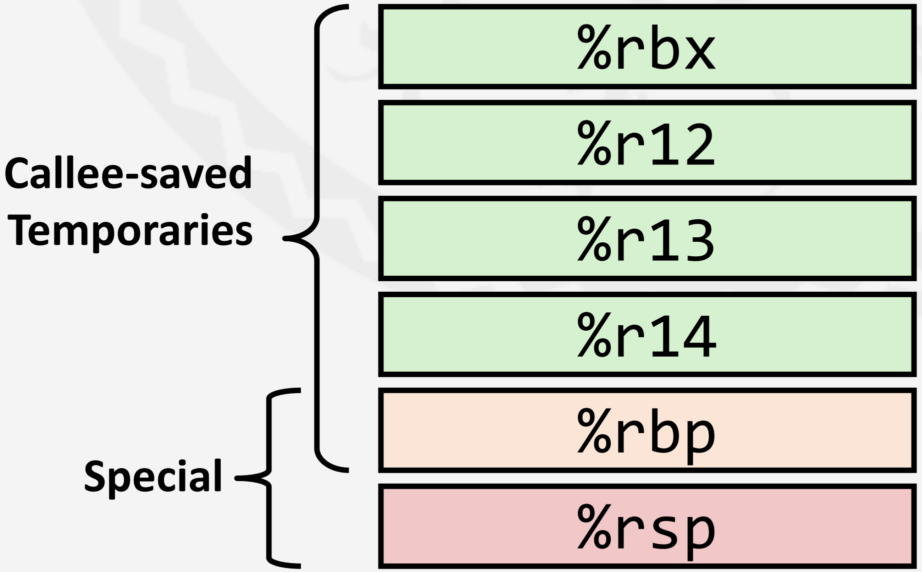
- %rax
  - 返回值
    Return value
- %rdi, ..., %r9
  - 参数
    Arguments



x86-64 Linux 中寄存器的用途 #2
x86-64 Linux Register Usage #2

- `%rbx, %r12, %r13, %r14, %rbp, %rsp`
  - 被调用者保护
    Callee-saved
  - 被调用者必须保护和恢复（如果被调用者使用）
    Callee must save & restore

- `%rbp`
  - 可以用于存储指向栈底指针
    May be used as frame pointer
  - 也可用用作普通临时数据的存储
    Arguments
- `%rsp`
  - 特殊的调用者保护形式
    Special form of callee save
  - 过程返回前恢复
    Restored to original value upon exit from procedure



过程调用规范

Passing Control

举例：被调用者保护 #1
Callee-Saved Example #1

```c
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
call_incr2:
  pushq   %rbx
  subq    $16, %rsp
  movq    %rdi, %rbx
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    %rbx, %rax
  addq    $16, %rsp
  popq    %rbx
  ret
```

Initial Stack Structure

Stack	
...	
Rtn address	← %rsp

Resulting Stack Structure

Stack	
...	
Rtn address	
Saved %rbx	
15213	← %rsp+8
Unused	← %rsp

过程调用规范

Passing Control

举例：被调用者保护 #2
Callee-Saved Example #2

```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
call_incr2:
  pushq   %rbx
  subq    $16, %rsp
  movq    %rdi, %rbx
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    %rbx, %rax
  addq    $16, %rsp
  popq    %rbx
  ret
```

Resulting Stack Structure

Stack	
. . .	
Rtn address	
Saved %rbx	
15213	← %rsp+8
Unused	← %rsp

Pre-return Stack Structure

Stack	
. . .	
Rtn address	← %rsp

本章内容

Topic

- 栈的结构

  Stack Structure

- 过程调用规范

  Calling Conventions

- 递归

  Recursion

递归函数
Recursive Function

```c
/* Recursive popcount */
long pcount_r(unsigned long x)
{
  if (x == 0)
    return 0;
  else
    return (x & 1) + pcount_r(x >> 1);
}
```

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

递归函数的出口
Recursive Function Terminal Case

```c
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

Register	Use(s)	Type
%rdi	x	Argument
%rax	Return value	Return value

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

递归函数的寄存器保护
Recursive Function Register Save

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1) + pcount_r(x >> 1);
}
```

Register	Use(s)	Type
%rdi	x	Argument

...
Rtn address
Saved %rbx ← %rsp

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

递归函数的调用前的准备
Recursive Function Call Setup

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1) + pcount_r(x >> 1);
}
```

Register	Use(s)	Type
%rdi	x >> 1	Rec. argument
%rbx	x & 1	Callee-saved

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

递归函数的调用
Recursive Function Call

```c
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1) + pcount_r(x >> 1);
}
```

Register	Use(s)	Type
%rbx	x & 1	Callee-saved
%rax	Recursive call return value	

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

递归

Recursion

递归函数的结果
Recursive Function Result

```c
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1) + pcount_r(x >> 1);
}
```

Register	Use(s)	Type
%rbx	x & 1	Callee-saved
%rax	Return value	

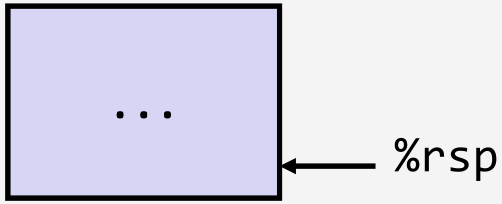
```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

递归函数的结束
Recursive Function Completion

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1) + pcount_r(x >> 1);
}
```

Register	Use(s)	Type
%rax	Return value	Return value

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```



对递归函数的观察
Observations About Recursion

- 和普通函数调用相比并没有什么特殊的处理
  Handled Without Special Consideration
  - 栈帧：每次函数调用都会分配一个私有的存储空间
    Stack frames mean that each function call has private storage
    - 保存寄存器和局部变量
      Saved registers & local variables
    - 保存返回地址
      Saved return pointer
  - 寄存器使用惯例保证了一次函数调用不会破坏其他函数的数据
    Register saving conventions prevent one function call from corrupting another's data
  - 栈与过程调用返回在工作模式上完美契合
    Stack discipline follows call / return pattern
    - 如果 P 调用 Q，则 Q 先于 P 返回
      If P calls Q, then Q returns before P
    - 后进先出
      Last-In, First-Out

- 同样也适用于相互递归
  Also works for mutual recursion
  - P 调用 Q；Q 调用 P
    P calls Q; Q calls P

X86-64 过程总结
x86-64 Procedure Summary

- 要点
  Important Points
- 对于过程的调用与返回，栈是一种恰当的数据结构
  Stack is the right data structure for procedure call / return
  - 如果 P 调用 Q，则 Q 先于 P 返回
    If P calls Q, then Q returns before P
- 递归和普通函数调用的处理方式相同
  Recursion (& mutual recursion) handled by normal calling conventions
- 指针是地址的值
  Pointers are addresses of values