Machine-Level Programming: Procedures

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Today

- Recursion
- Recursive procedures

Recursion

- **Recursion is a method where the solution to a problem depends on solutions to smaller instances of the same problem (as opposed to iteration)**

- **Most computer programming languages support recursion by allowing a function to call itself**
  - Some functional programming languages do not define any looping constructs but rely solely on recursion to repeatedly call code

- **Recursive techniques can often present simple and elegant solutions to problems**

Recursion

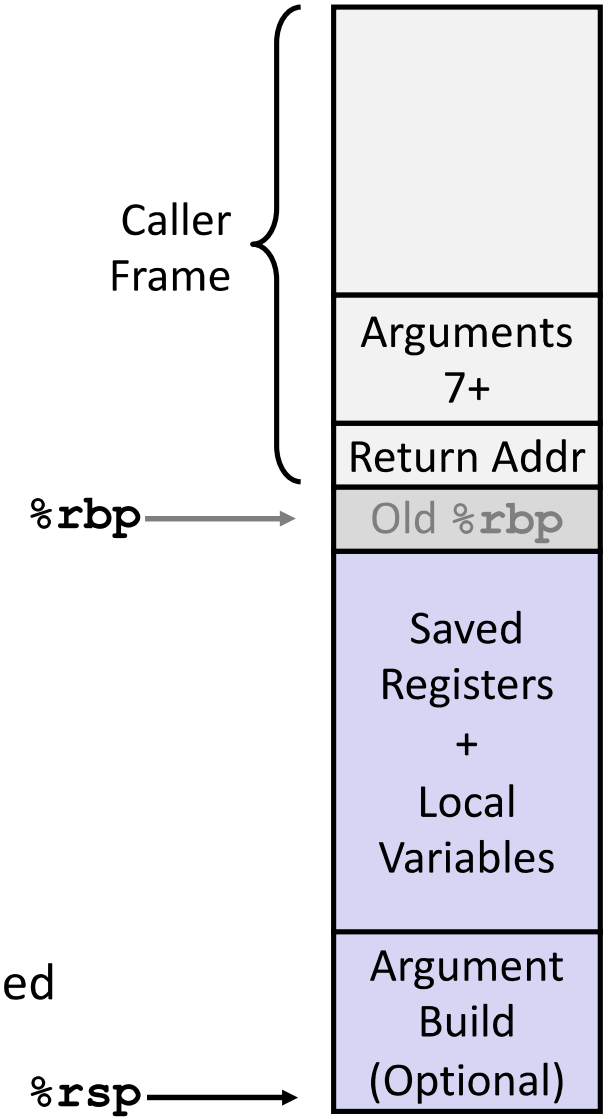
- **A recursive function definition has one or more *base cases*, and one or more *recursive cases***

- **The base case**
  - A small problem that we know how to solve and is the case that causes the recursion to end
  - The function produces a result trivially (without recurring)

- **The recursive case**
  - The more general case of the problem we're trying to solve
  - The function recurs (calls itself)
  - The recursive call must always be to a case that makes progress toward a base case

Stack support

- **The stack conventions described in the previous lectures allow procedures to call themselves recursively**
- **Each call has its own private space on the stack**
  - The local variables of the multiple calls do not interfere with one another
- **The stack discipline naturally provides the proper policy for:**
  - Allocating local storage when the procedure is called
  - Deallocating it when it returns



Call chain

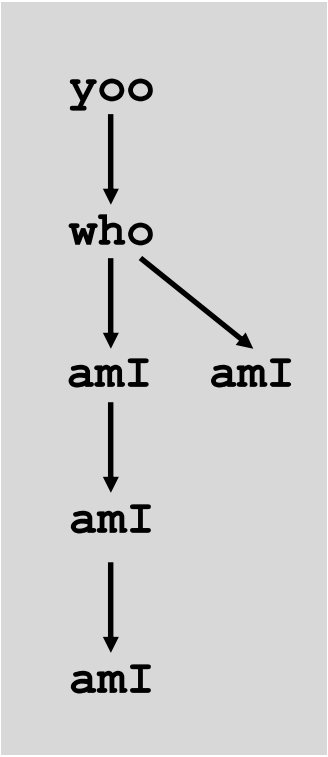
```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```

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

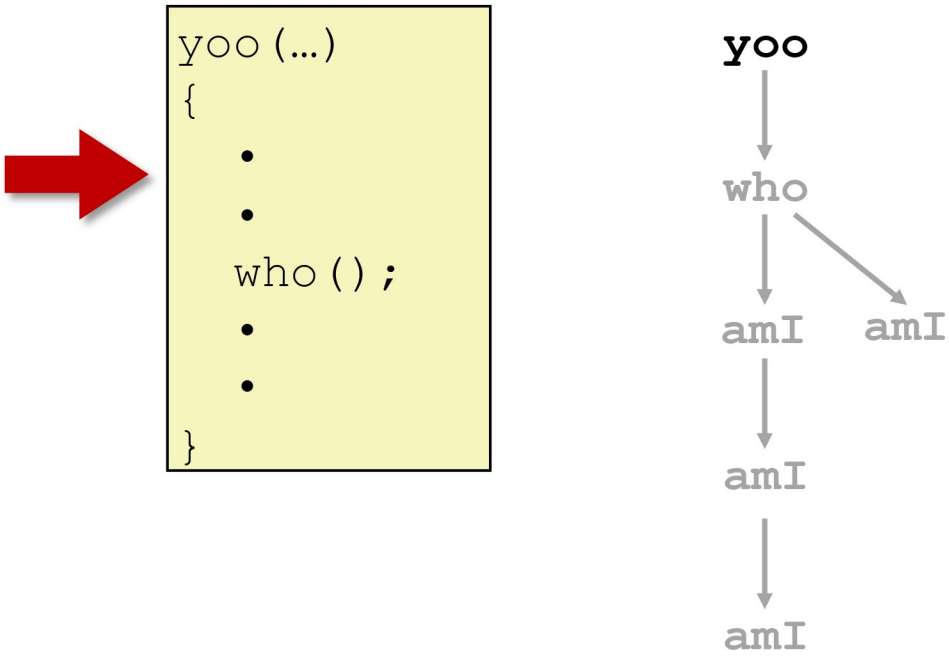
```
amI(…)
{
   •
   •
   amI();
   •
   •
}
```

Procedure **amI()** is recursive

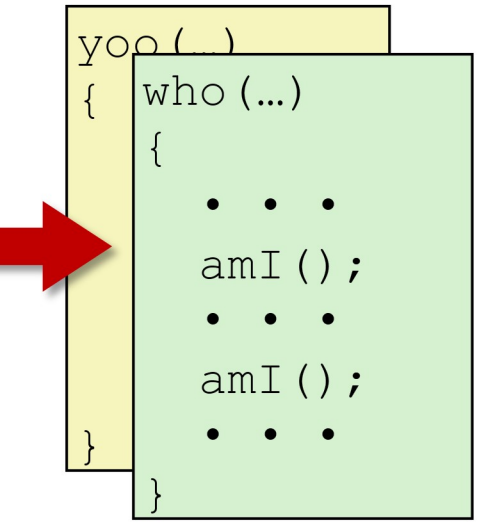
Call chain example

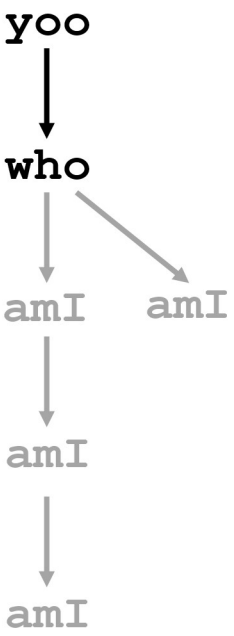


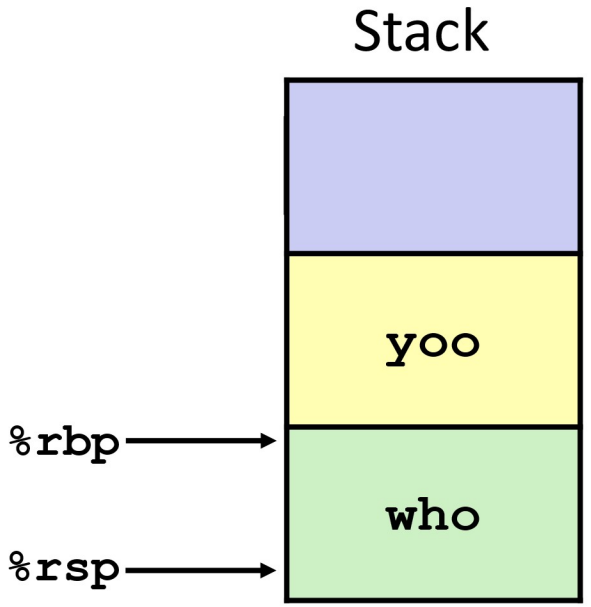
Call chain example



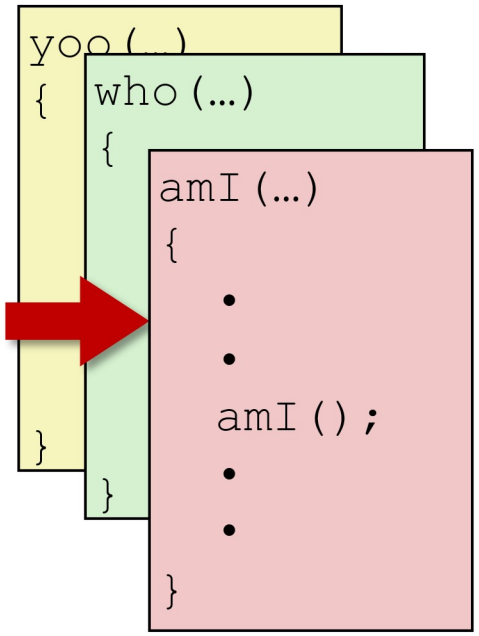
Call chain example

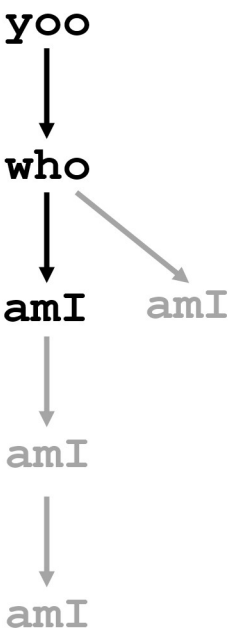


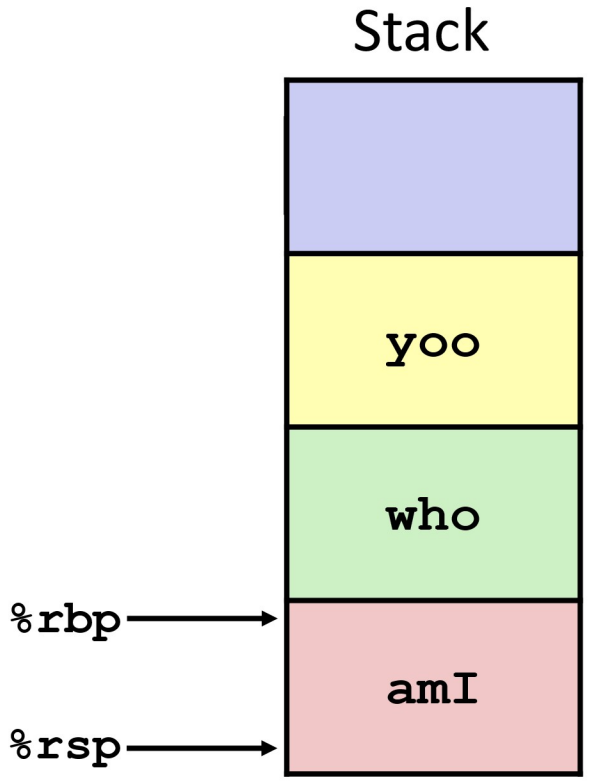




Call chain example







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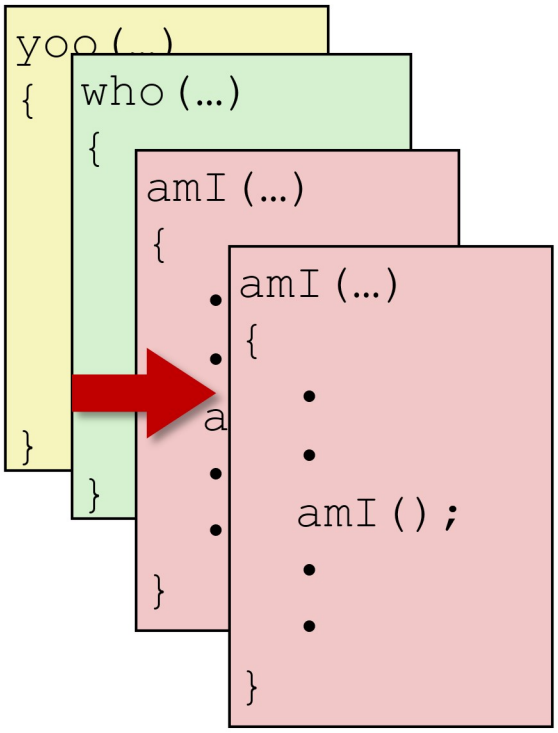

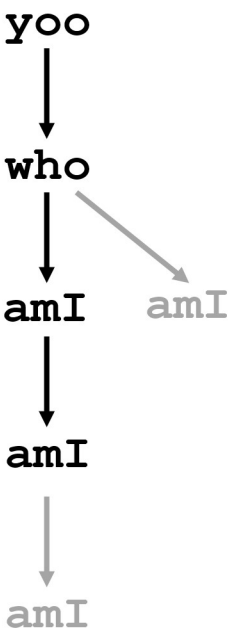

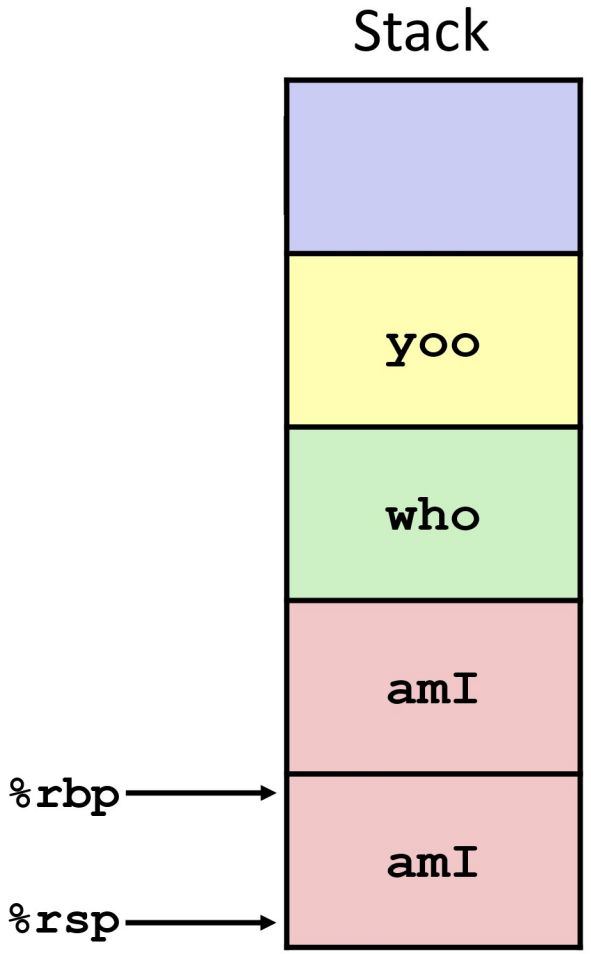

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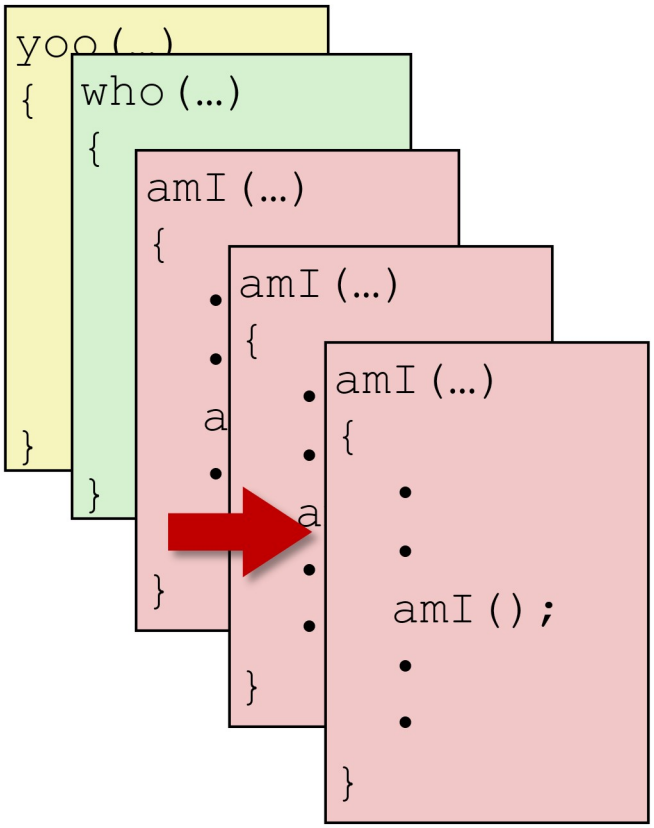

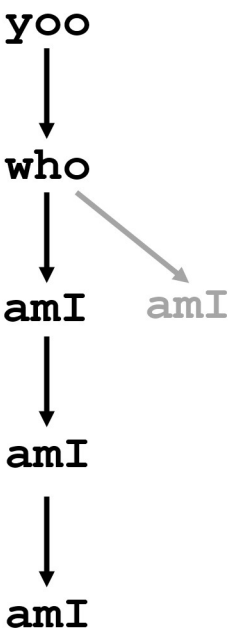

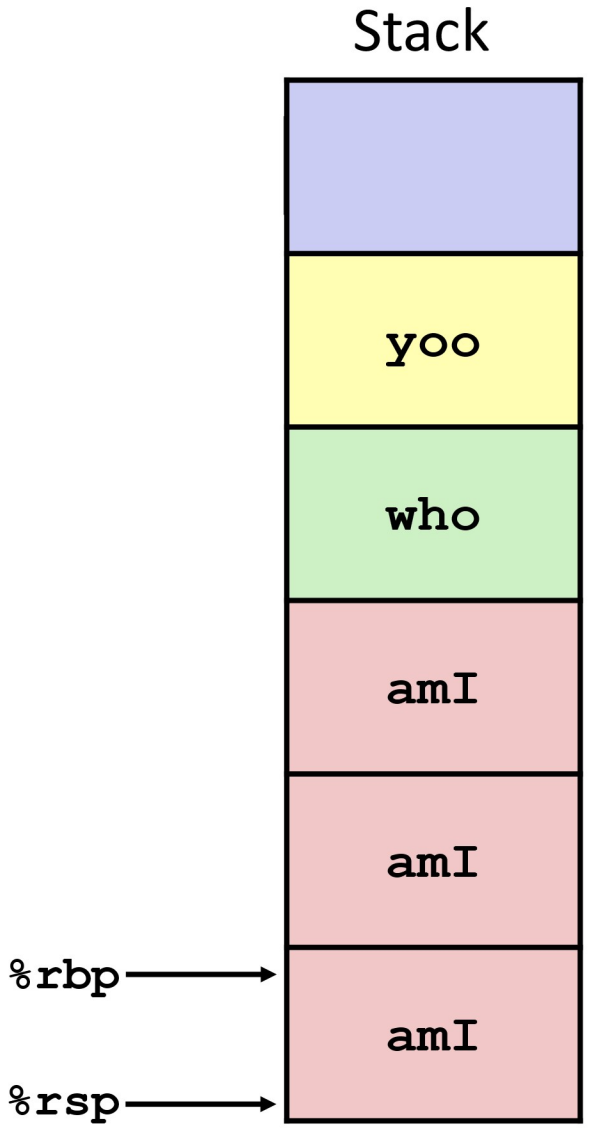

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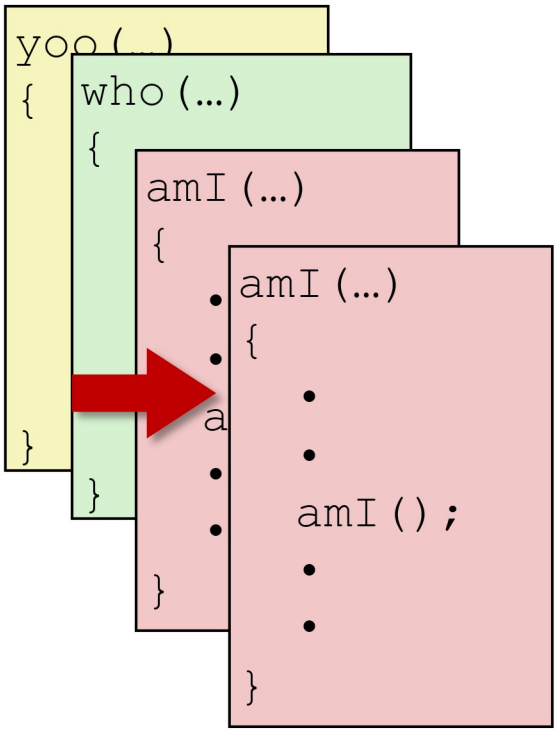

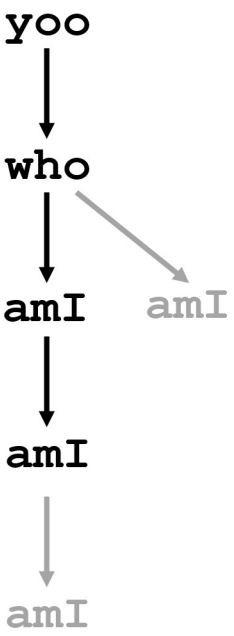

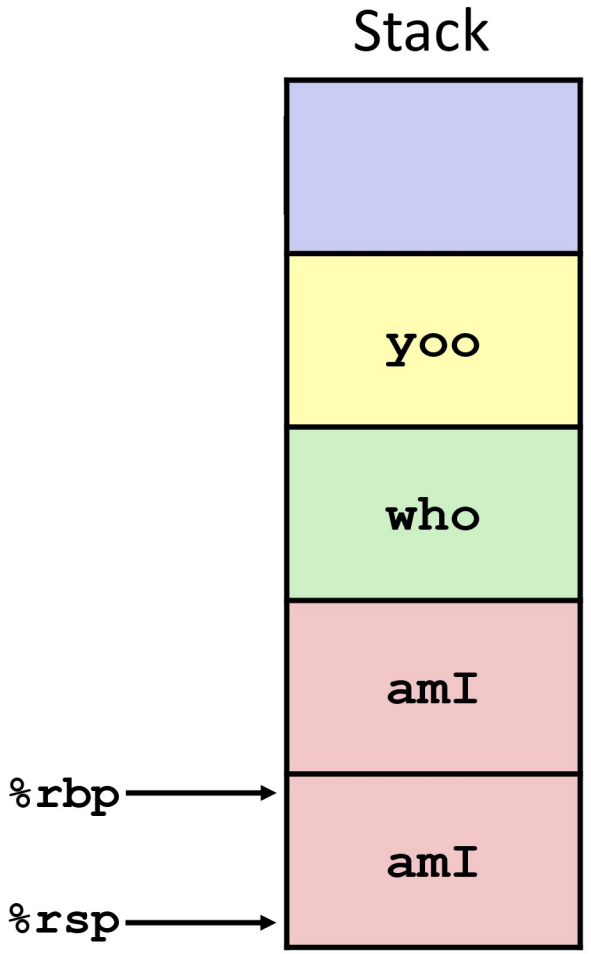

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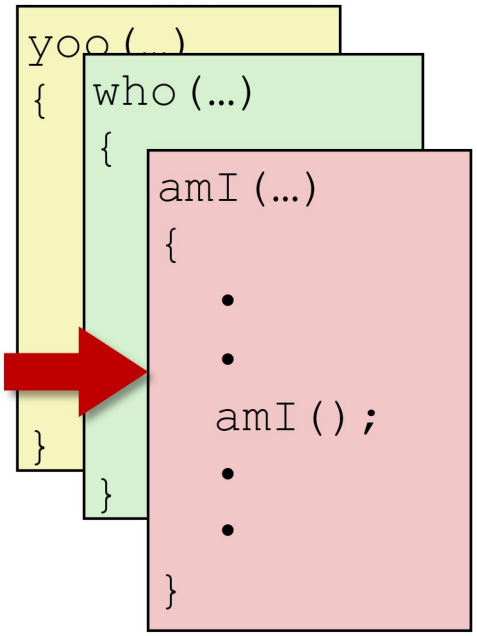

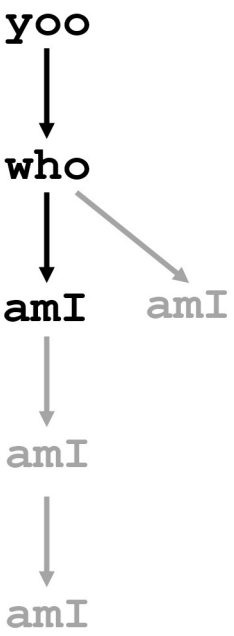

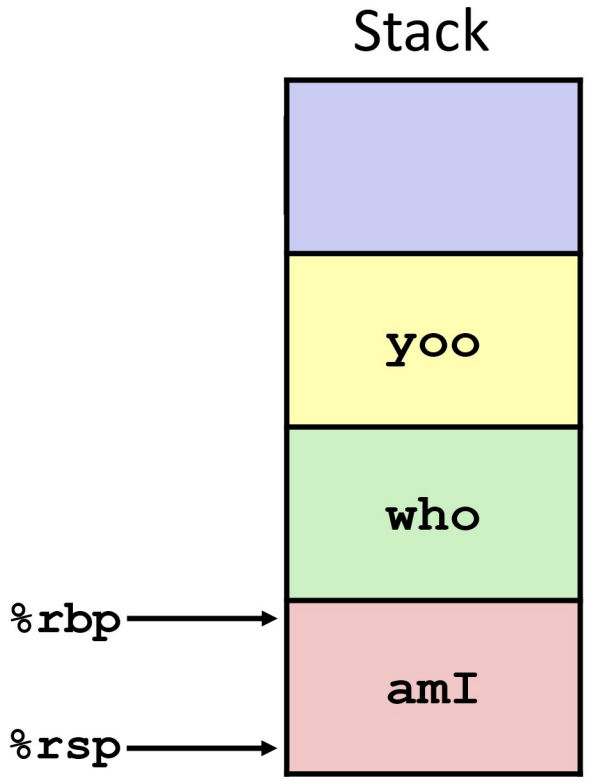

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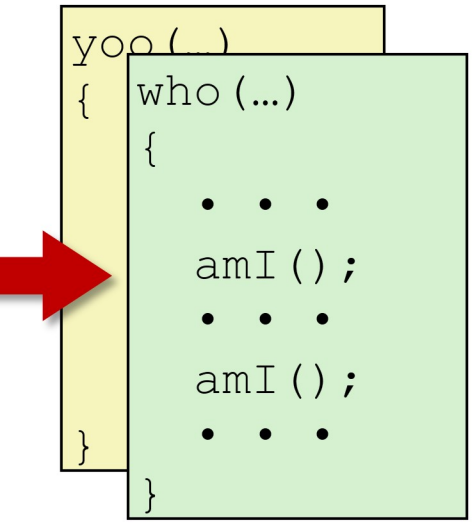

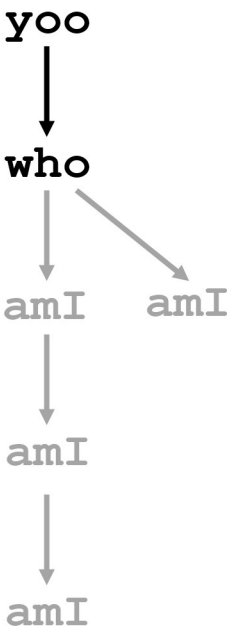

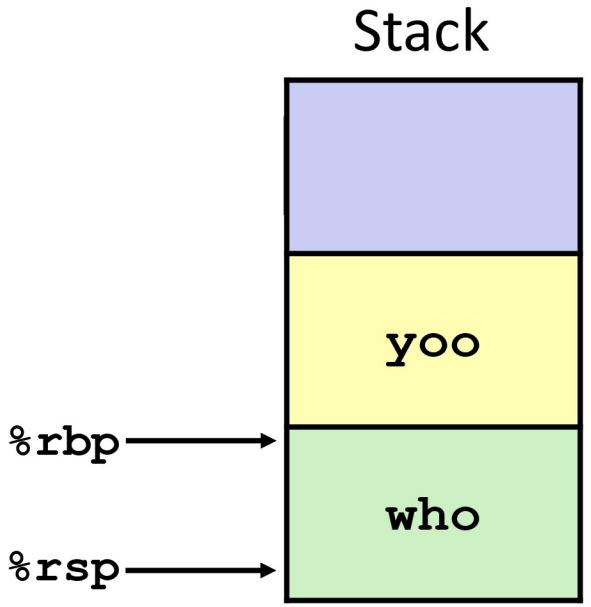

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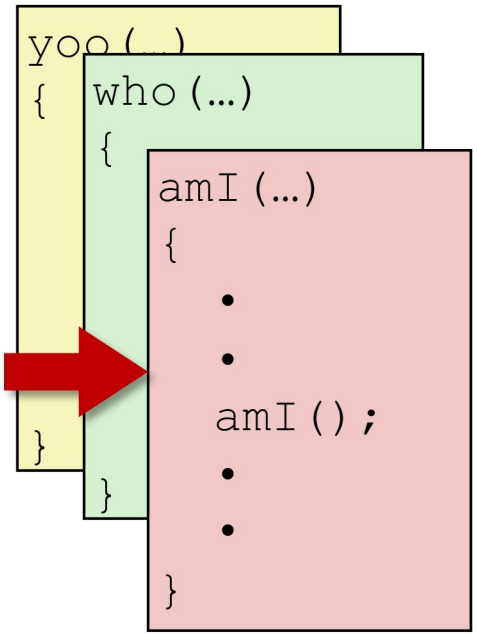

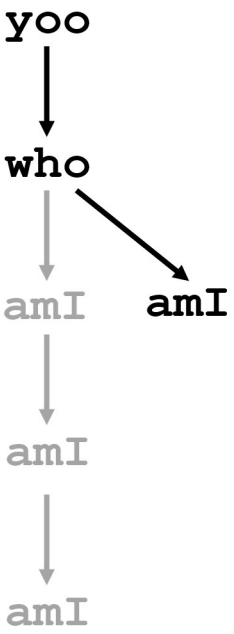

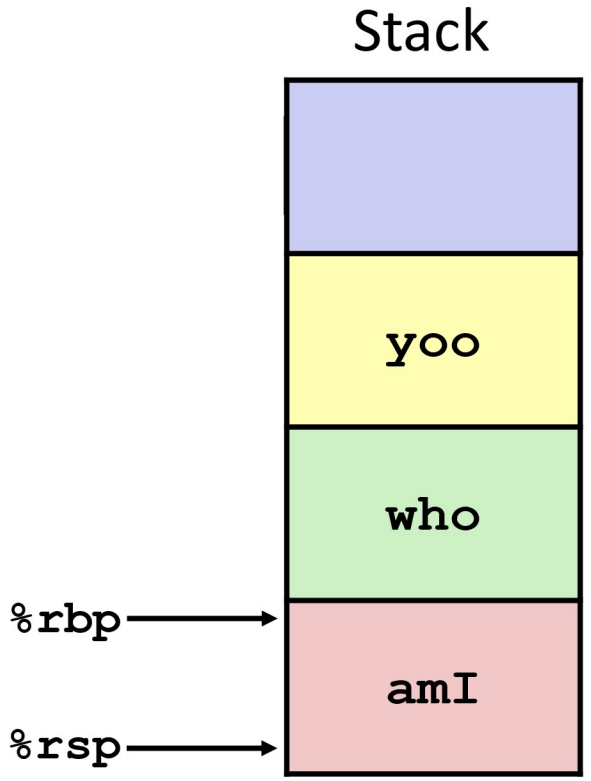

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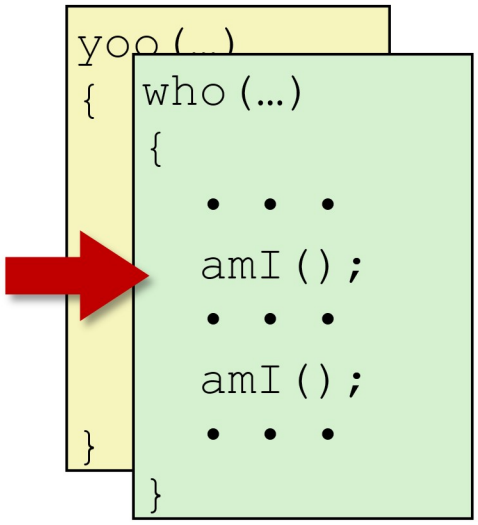

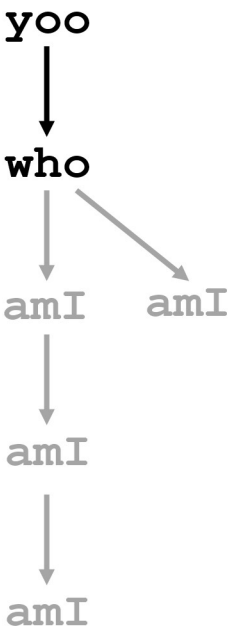

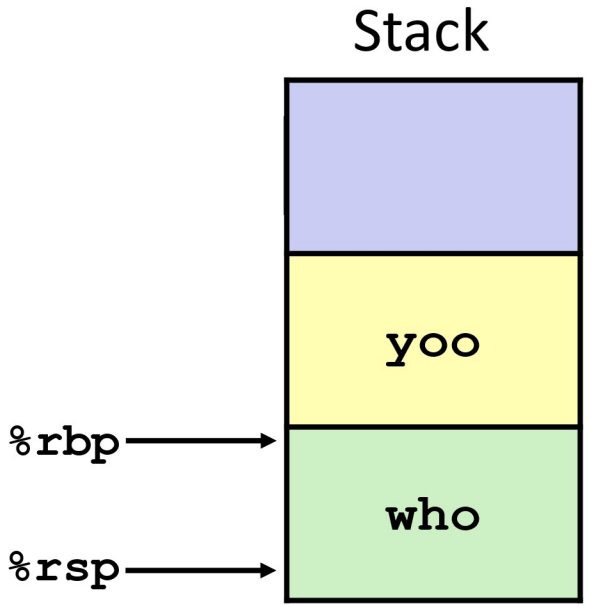

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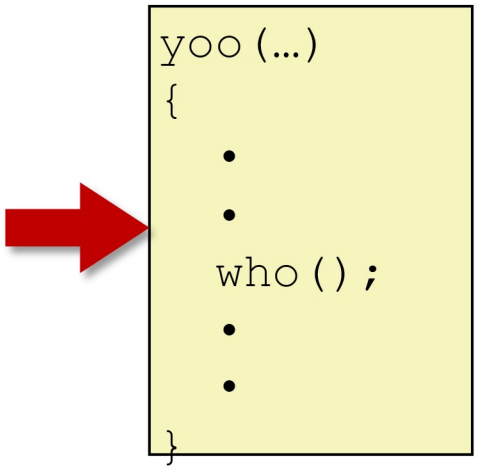
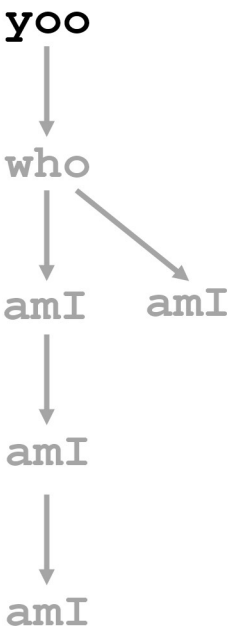
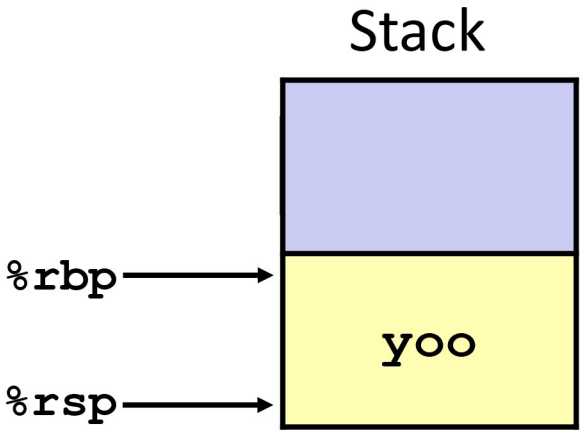






Today

- Recursion
- **Recursive procedures**

Recursive procedures

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

```
pcount_r:
  movq    $0, %rax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andq    $1, %rbx
  shrq    %rdi
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

Recursive procedures: Base case

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

```
pcount_r:
  movq    $0, %rax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andq    $1, %rbx
  shrq    %rdi
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

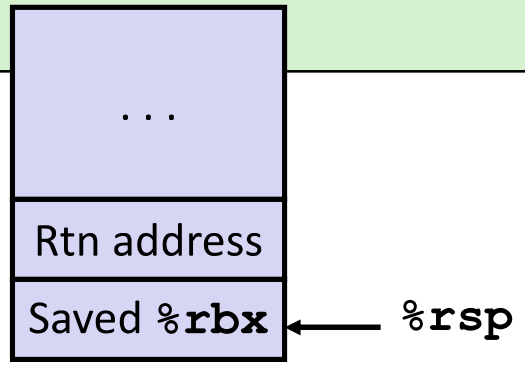
Register	Use(s)	Type
%rdi	x	Argument
%rax	Return value	Return value

Recursive procedures: Register saving

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

```
pcount_r:
  movq    $0, %rax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andq    $1, %rbx
  shrq    %rdi
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

Register	Use(s)	Type
%rdi	x	Argument



Recursive procedures: Call setup

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

```
pcount_r:
  movq    $0, %rax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andq    $1, %rbx
  shrq    %rdi
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

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

Recursive procedures: Call

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

```
pcount_r:
  movq    $0, %rax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andq    $1, %rbx
  shrq    %rdi
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

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

Recursive procedures: Result

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

```
pcount_r:
  movq    $0, %rax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andq    $1, %rbx
  shrq    %rdi
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

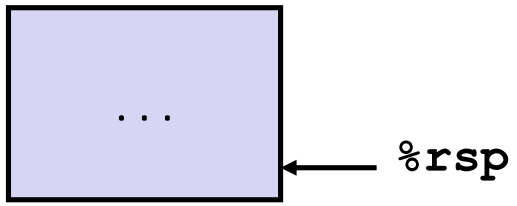
Register	Use(s)	Type
%rbx	**x & 1**	Callee-saved
%rax	Return value	

Recursive procedure: Completion

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

```
pcount_r:
  movq    $0, %rax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andq    $1, %rbx
  shrq    %rdi
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

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



Observations about recursion

- **Handled without special consideration**
  - Stack frames mean that each function call has private storage
    - Saved registers and local variables
    - Saved return pointer
- **Register saving conventions prevent one function call from corrupting another's data**
  - Stack discipline follows call / return pattern
    - If P calls Q, then Q returns before P
    - Last-In, First-Out
- **Also works for mutual recursion**
  - P calls Q; Q calls P