CS406: Compilers

Spring 2022

Week 9: IR Code for Functions, Local Optimizations

Slides Acknowledgements: Milind Kulkarni

Functions Typical Syntax and Usage

```
FUNCTION VOID bar(INT x, FLOAT y) BEGIN

END
```

Keywords

Return type

comma separated parameter declarations.

Declarations (string or variable decl) followed by statement declarations

```
FUNCTION void foo() BEGIN
INT a;
FLOAT b;
…
bar(a, b);

END
```

Calls function bar

Terms

```
void foo() {
  int a, b;
  ...
  bar(a, b);
}

void bar(int x, int y) {
    ...
}
```

- foo is the *caller*
- bar is the *callee*
- a, b are the *actual parameters* to bar
- x, y are the *formal parameters* of bar
- Shorthand:
  - argument = actual parameter
  - parameter = formal parameter

Different Kinds of Parameters

- Value
- Reference
- Result
- Value-Reference
- Read-only
- Call-by-Name

Value parameters

- "Call-by-value"
- Used in C, Java, default in C++
- Passes the value of an argument to the function
- Makes a copy of argument when function is called
- Advantages? Disadvantages?

Advantage: 'side-effect' free – caller can be sure that the argument is not modified by the callee

Disadvantage: Not efficient for larger sized arguments.

Value parameters

```
int x = 1;
void main () {
    foo(x, x);
    print(x);
}

void foo(int y, int z) {
    y = 2;
    z = 3;
    print(x);
}
```

- What do the print statements print?

Reference parameters

- "Call-by-reference"
- Optional in Pascal (use "var" keyword) and C++ (use "&")
- Pass the *address* of the argument to the function
- If an argument is an expression, evaluate it, place it in memory and then pass the address of the memory location
- Advantages? Disadvantages?

Advantage: Efficiency – for larger sized arguments
Disadvantage: results in clumsy code at times (e.g. check for null pointers)

Reference parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int &y, int &z) {
   y = 2;
   z = 3;
   print(x);
   print(y);
}
```

- What do the print statements print?

Result Parameters

- To capture the return value of a function
- Copied at the end of function into arguments of the caller
- E.g. `output` ports in Verilog `module` definitions

Result Parameters

```
int x = 1
void main () {
  foo(x, x);
  print(x);
}

void foo(int y, result int z) {
  y = 2;
  z = 3;
  print(x);
}
```

- What do the print statements print?

Value-Result Parameters

- “Copy-in copy-out”
- Evaluate argument expression, copy to parameters
- After subroutine is done, copy values of parameters back into arguments
- Results are often similar to pass-by-reference, but there are some subtle situations where they are different

Value-Result Parameters

```
int x = 1
void main () {
  foo(x, x);
  print(x);
}

void foo(int y, value result int z)
{
  y = 2;
  z = 3;
  print(x);
}
```

- What do the print statements print?

Read-only Parameters

- Used when callee will not change value of parameters
- Read-only restriction must be enforced by compiler
- E.g. `const` parameter in C/C++
- Enforcing becomes tricky when in the presence of aliasing and control flow. E.g.

```
void foo(readonly int x, int y) {
int * p;
if (...) p = &x else p = &y
*p = 4
}
```

Call-by-name Parameters

- The arguments are passed to the function before evaluation
  - Usually, we evaluate the arguments before passing them
- Not used in many languages, but Haskell uses a variant

```
int x = 1
void main () {
    foo(x+2);
    print(x);
}

void foo(int y) {
    z = y + 3; //expands to z = x + 2 + 3
    print(z);
}
```

Call-by-name Parameters

- Why is this useful?
  - E.g. to analyze certain properties of a program/function – termination

```
void main () {
    foo(bar());
}

void foo(int y) {
    z = 3;
    if(z > 3)
        z = y + z;
}
```

  - Even if `bar` has an infinite loop, the program terminates.

Program Layout in Memory

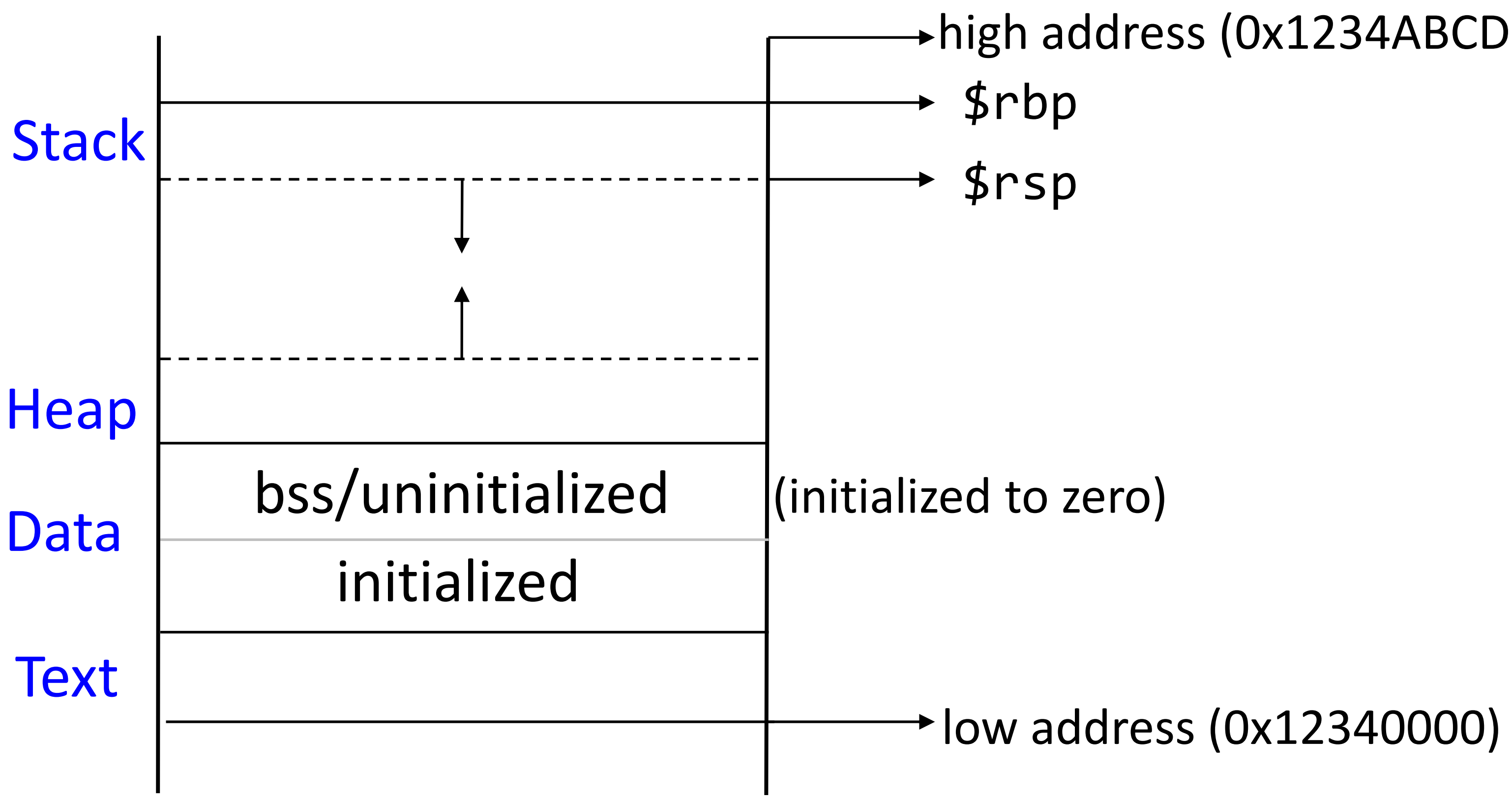
- Compiler assumes a *runtime environment* for execution of the program.
- A C/C++ program in Linux OS has 4 segments of memory
  - Every memory location is a *box* holding *data/instruction*

Program Layout in Memory

- A program's memory space is divided into four segments:

  1. Text
     - source code of the program
  2. Data
     - Broken into *uninitialized* and *initialized* segments; contains space for global and static variables. E.g. `int x = 7; int y;`
  3. Heap
     - Memory allocated using `malloc/calloc/realloc/new`
  4. Stack
     - Function arguments, return values, local variables, special registers.

Program Layout in Memory



Activation

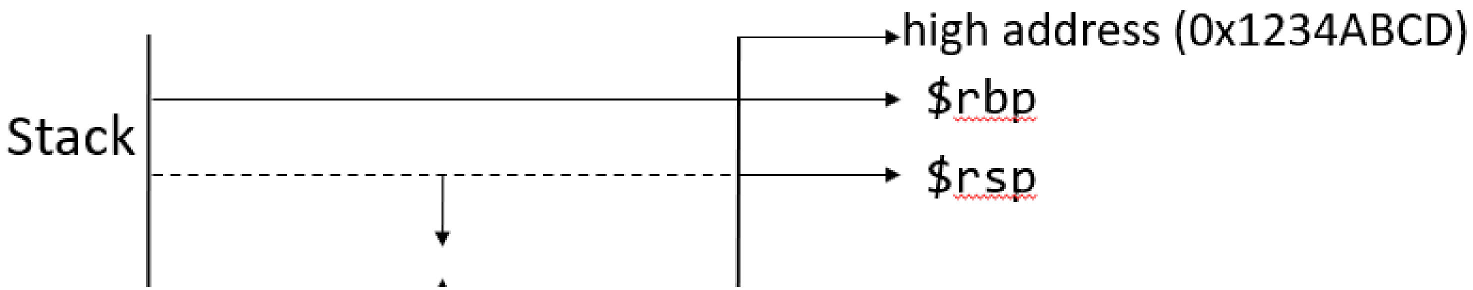
- A function call or invocation is termed an *activation*
- Calls to functions in a program form *activation tree*
  - Postorder traversal of the tree shows return sequence i.e. the order in which control returns from functions
  - Preorder traversal of the tree shows calling sequence
- In a sequential program, at any point in time, *control of execution is in any one activation*
  - All the ancestors of that activation are active i.e. have not returned

Activation

- Activations are managed through the help of *control stack*
- A function call (activation) results in allocating a chunk of memory called *activation record* or *frame* on the stack (also called *stack frame*)

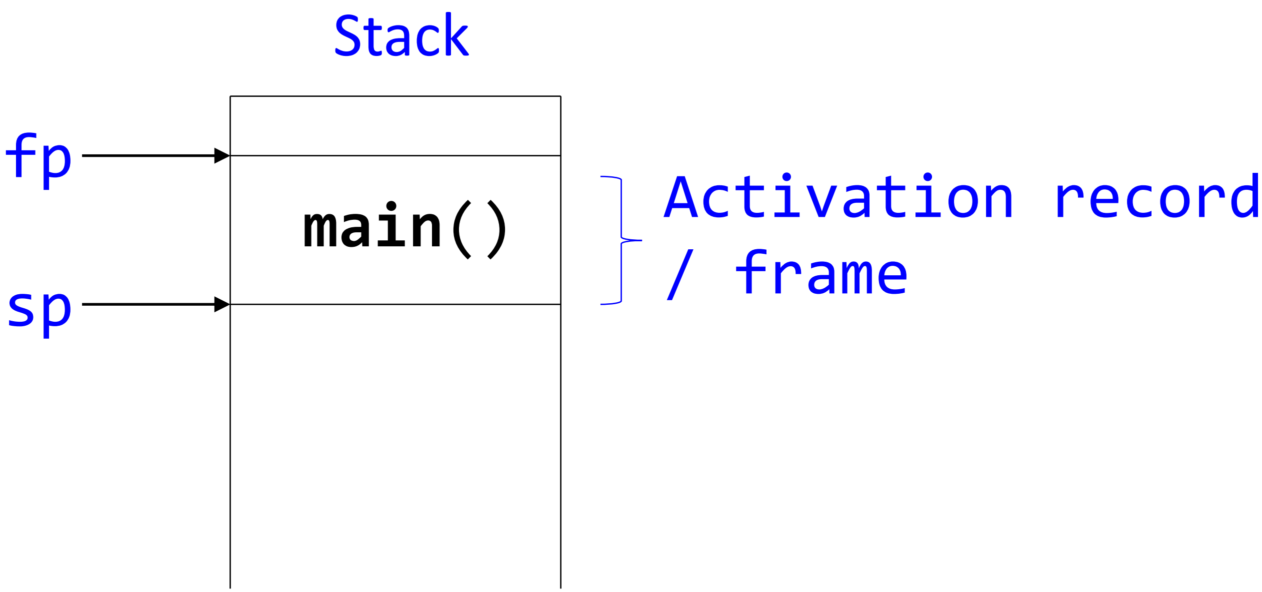
Activation Record

- A *sub-segment* of memory on the stack
  - Special registers `$rbp` and `$rsp` track the bottom and top of the stack frame. These are the names in x86 architecture.



- `$rbp` – base pointer or frame pointer (`fp`)
- `$rsp` – stack pointer (`sp`)

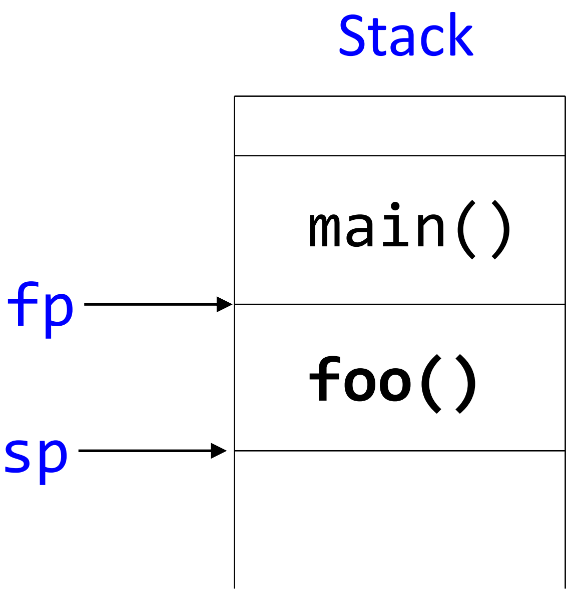
Activation Record - Example




```
main() {
    …
    foo();
    …
}

foo() {
    bar();
    …
    baz();
}
```

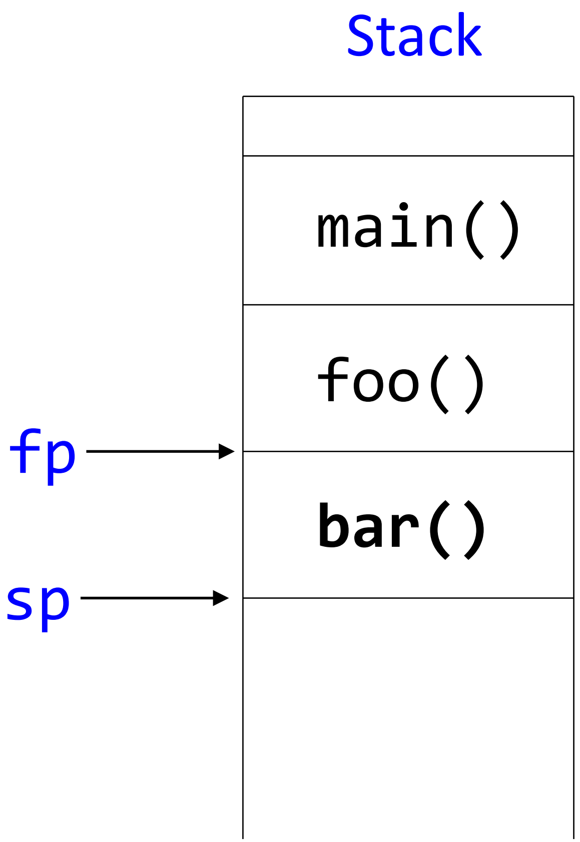
Activation Record - Example




```
main() {
   …
   foo();
   …
}

foo() {
   bar();
   …
   baz();
}
```

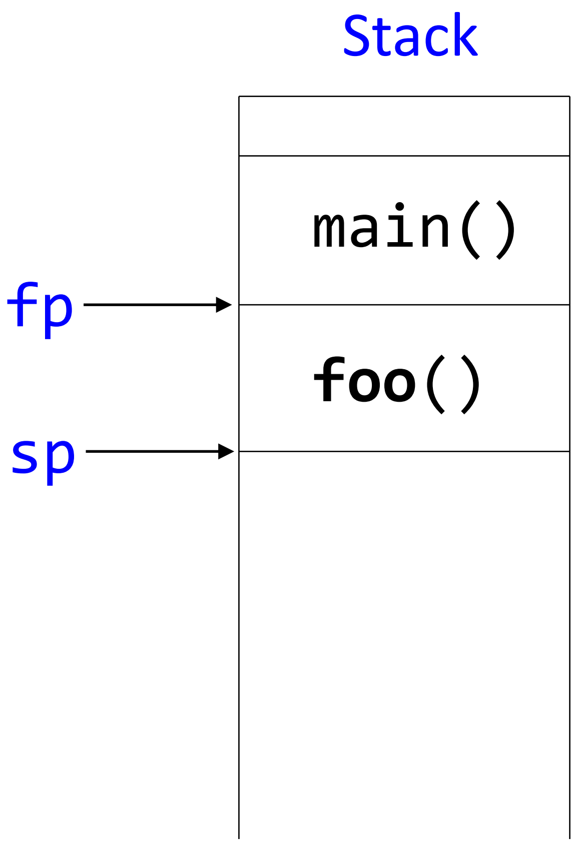
Activation Record - Example




```
main() {
   …
   foo();
   …
}

foo() {
   bar();
   …
   baz();
}
```

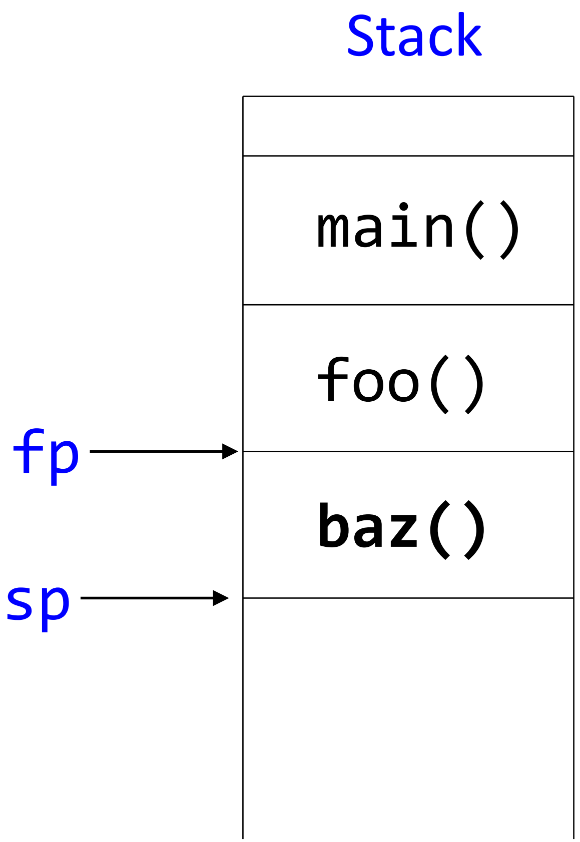
Activation Record - Example




```
main() {
   …
   foo();
   …
}

foo() {
   bar();
   …
   baz();
}
```

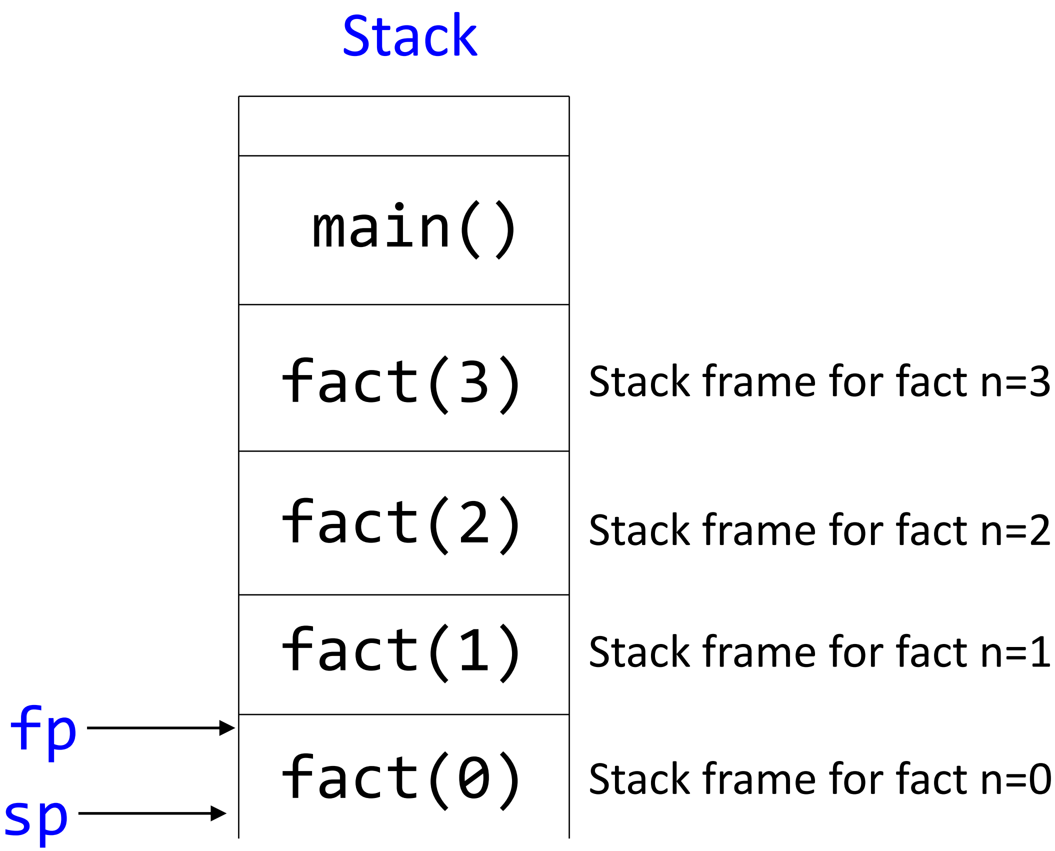
Activation Record - Example




```
main() {
    …
    foo();
    …
}

foo() {
    bar();
    …
    baz();
}
```

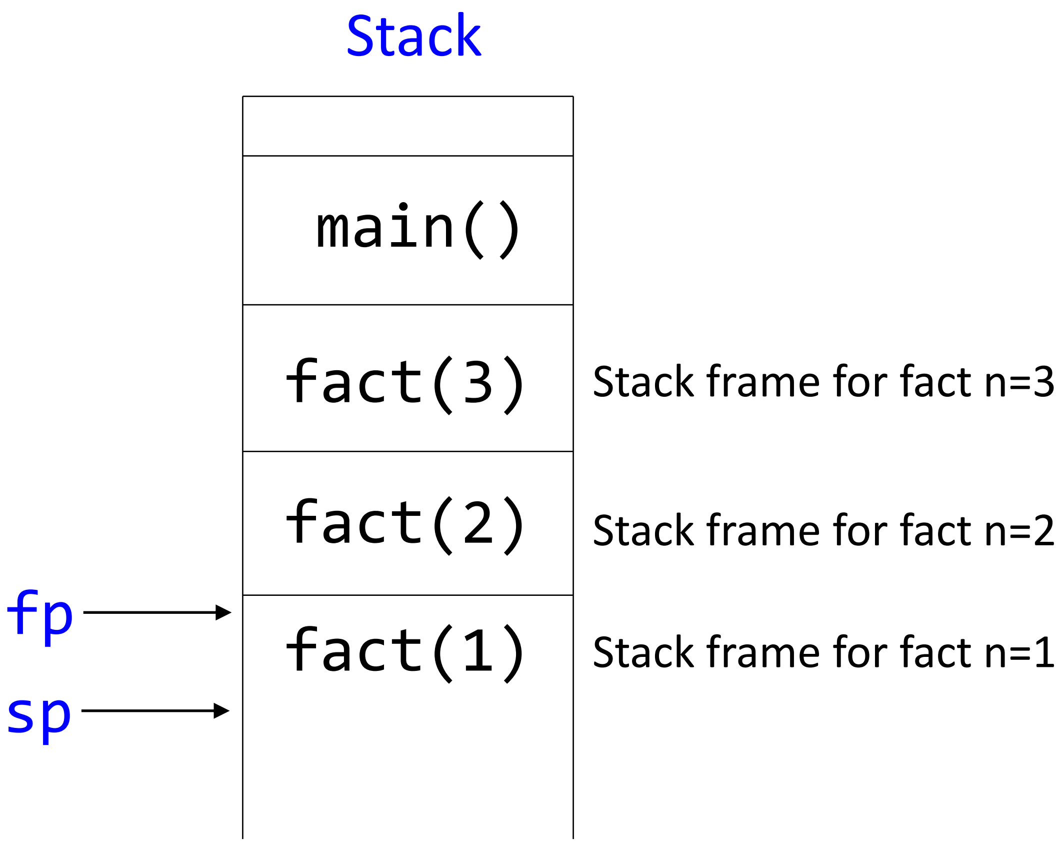
Activation Record – Example (Recursive Functions)




```
main() {
    …
    fact(3);
    …
}

fact(int n) {
if (n=0) return 1
return n*fact(n-1)
}
```

Activation Record – Example (Recursive Functions)

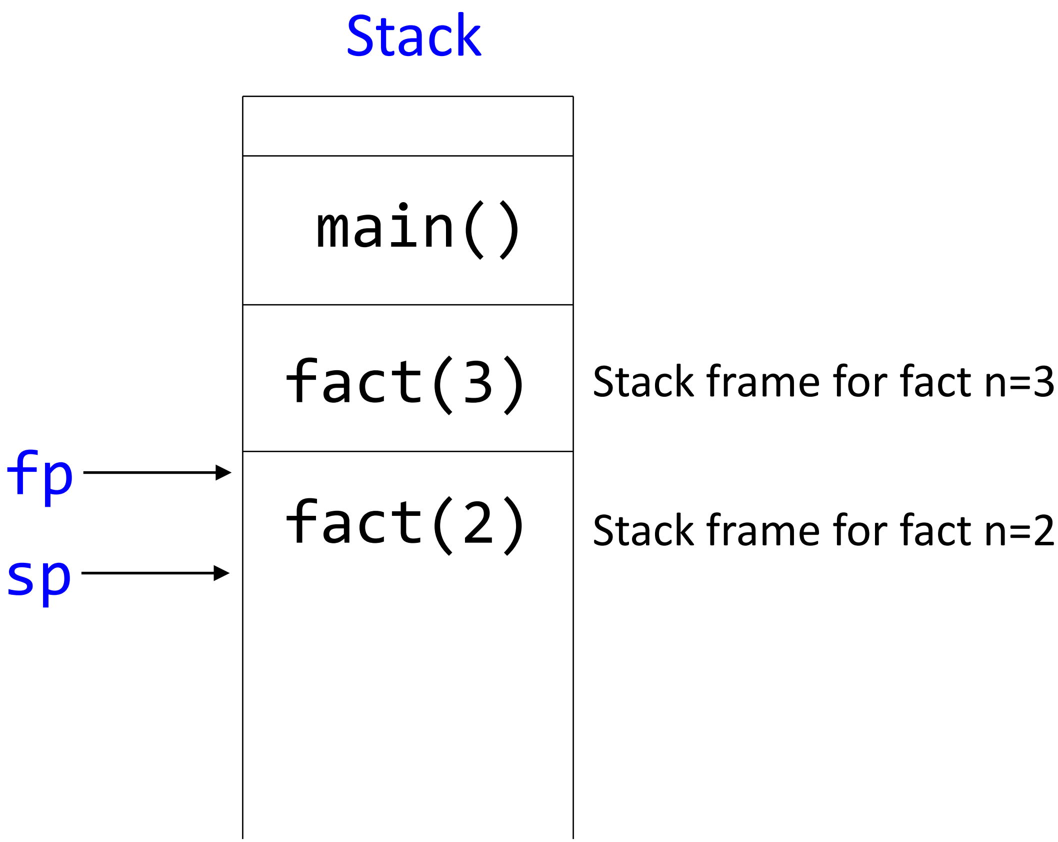



```
main() {
   …
   fact(3);
   …
}

fact(int n) {
if (n=0) return 1
return n*fact(n-1)
}
```

Stack frame for n=0 popped off. 1 Returned.

Activation Record – Example (Recursive Functions)

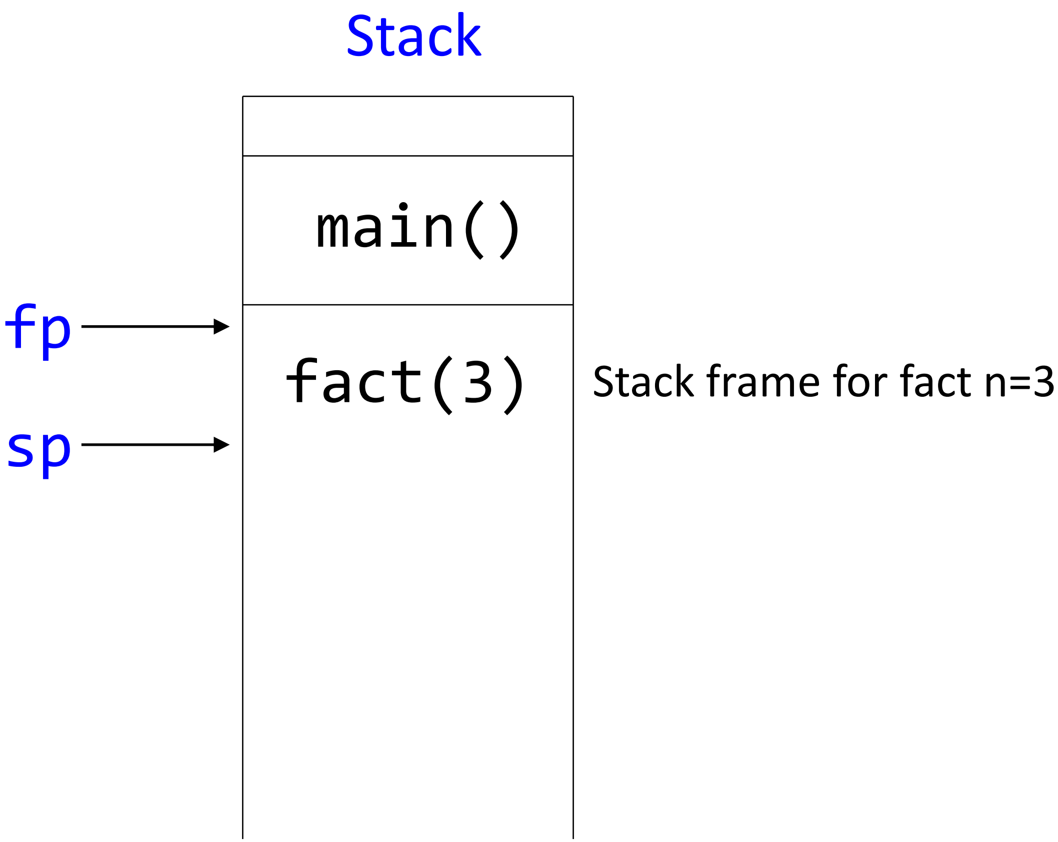



```
main() {
   …
   fact(3);
   …
}

fact(int n) {
if (n=0) return 1
return n*fact(n-1)
}
```

Stack frame for n=1 popped off. 1 Returned.

Activation Record – Example (Recursive Functions)

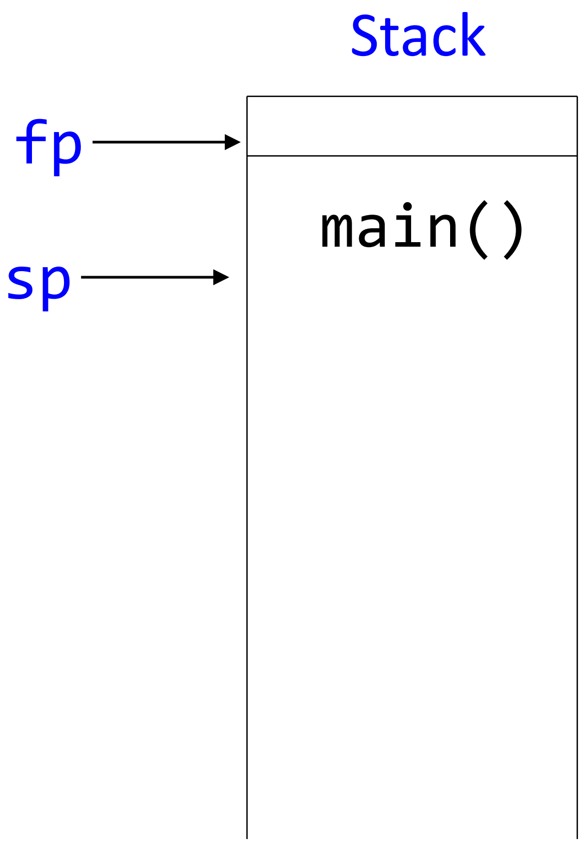



```
main() {
    …
    fact(3);
    …
}

fact(int n) {
if (n=0) return 1
return n*fact(n-1)
}
```

Stack frame for n=2 popped off. 2 Returned.

Activation Record – Example (Recursive Functions)




```
main() {
   …
   fact(3);
   …
}

fact(int n) {
if (n=0) return 1
return n*fact(n-1)
}
```

Stack frame for n=3 popped off. 6 Returned.

Activation Record

- What happens when a function is called?
  1. `fp` and `sp` get adjusted
  2. Memory for the activation record is allocated on stack
     - The size of the memory allocated depends on local variables used by the called function (consult function's symbol table for this)
  3. Each invocation of a function has its own instantiation of local variables
- When the function call returns:
  - Memory for the activation record is destroyed when the function returns

Activation Record

- What is stored in the activation record?

  Depends on the language being implemented:
  - Temporaries
  - Local vars
  - Saved registers
  - Return address, previous `fp`
  - Return value
  - Actual Params
- Who stores this information?
  - Caller
  - Callee

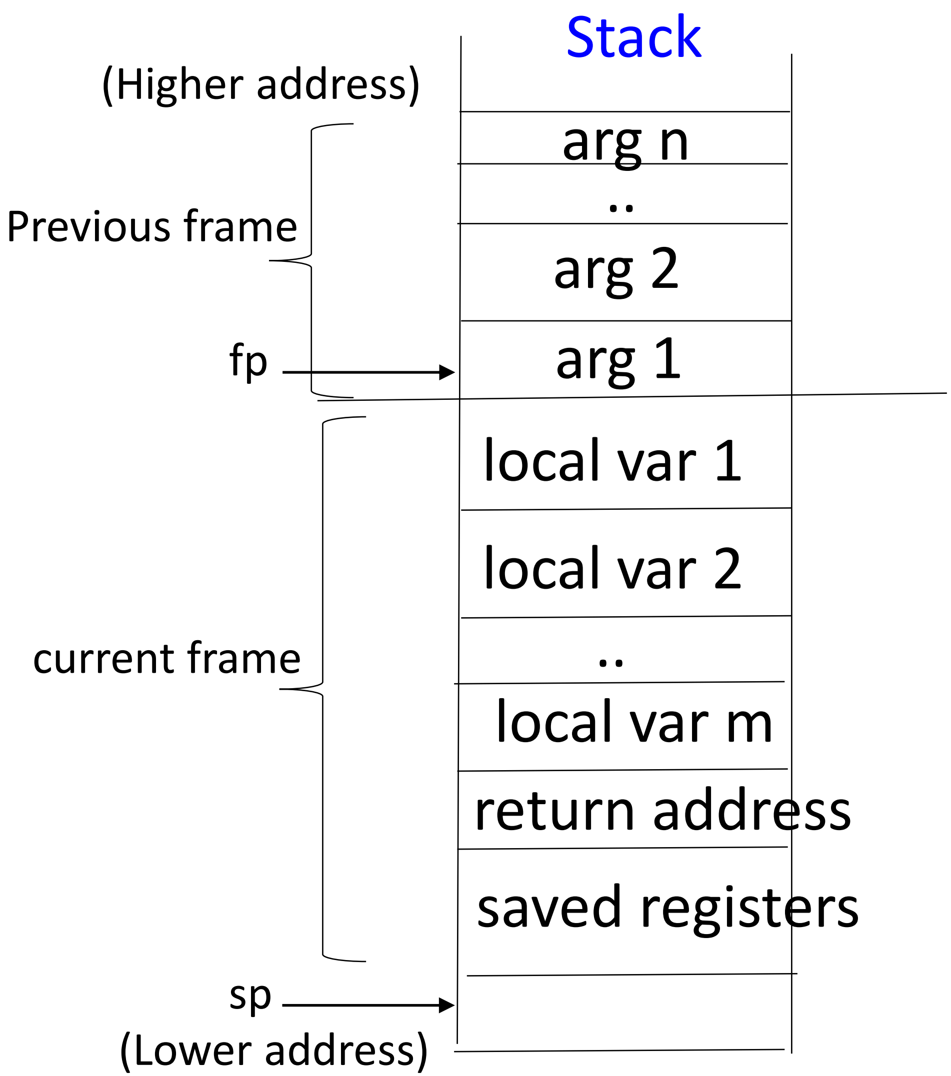
  together execute *calling sequence* and *return sequence*

Application Binary Interface (ABI)

- How is data organized on the activation record?
  - ABI is the specification on how data is provided to functions
    - Caller saves or callee saves
  - ABI is meant to deliver interoperability between different compilers
    - Compile the function using one compiler to create an object code, Link object code with other code compiled using a different compiler

form the *calling convention*

Typical Activation Record



Callee accesses arguments using +ve offset from FP:

argument1 = memory[FP]

argument2 = memory[FP+1] ..

Callee accesses local variables using –ve offset from FP:

local var 1=memory[FP-1]

local var 2=memory[FP-2]

Function call: Peeking at Activation Record

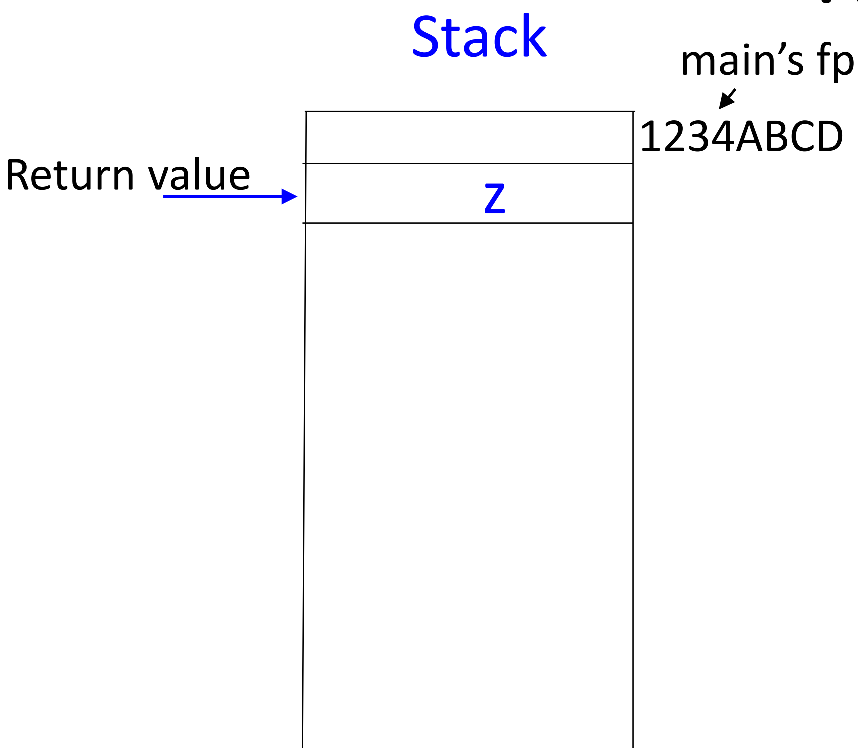
```
main() {
    …
    foo();
    …
}
```

- When `main` calls function `foo`
  1. The following are pushed on to the stack:
     1. `foo`'s arguments
     2. Space to hold `foo`'s return value
     3. Address of the next instruction executed (in `main`) when `foo` returns (return address)
     4. Current value of `$rbp` (frame pointer)

     `$rsp` is automatically updated (decremented) to point to current top of the stack.

  2. `$rbp` is assigned the value of `$rsp`

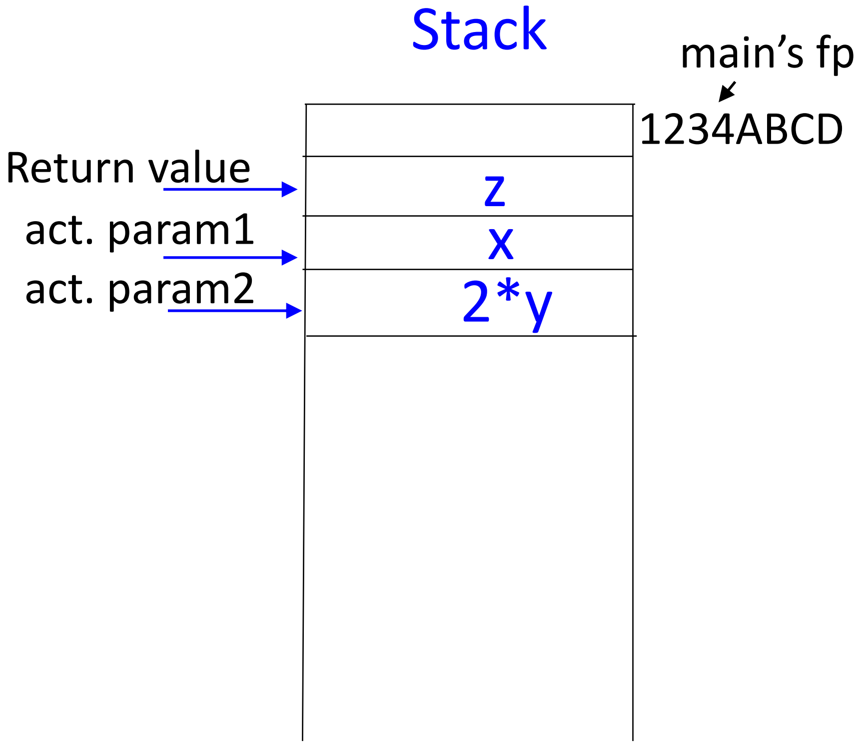
Function call: Peeking at Activation Record




```
main() {
   z=foo(x, 2*y);
   return;
}

int foo(int a, int b) {
   int l1, l2
   l1=a;
   l2=b;
   return l1+l2;
}
```

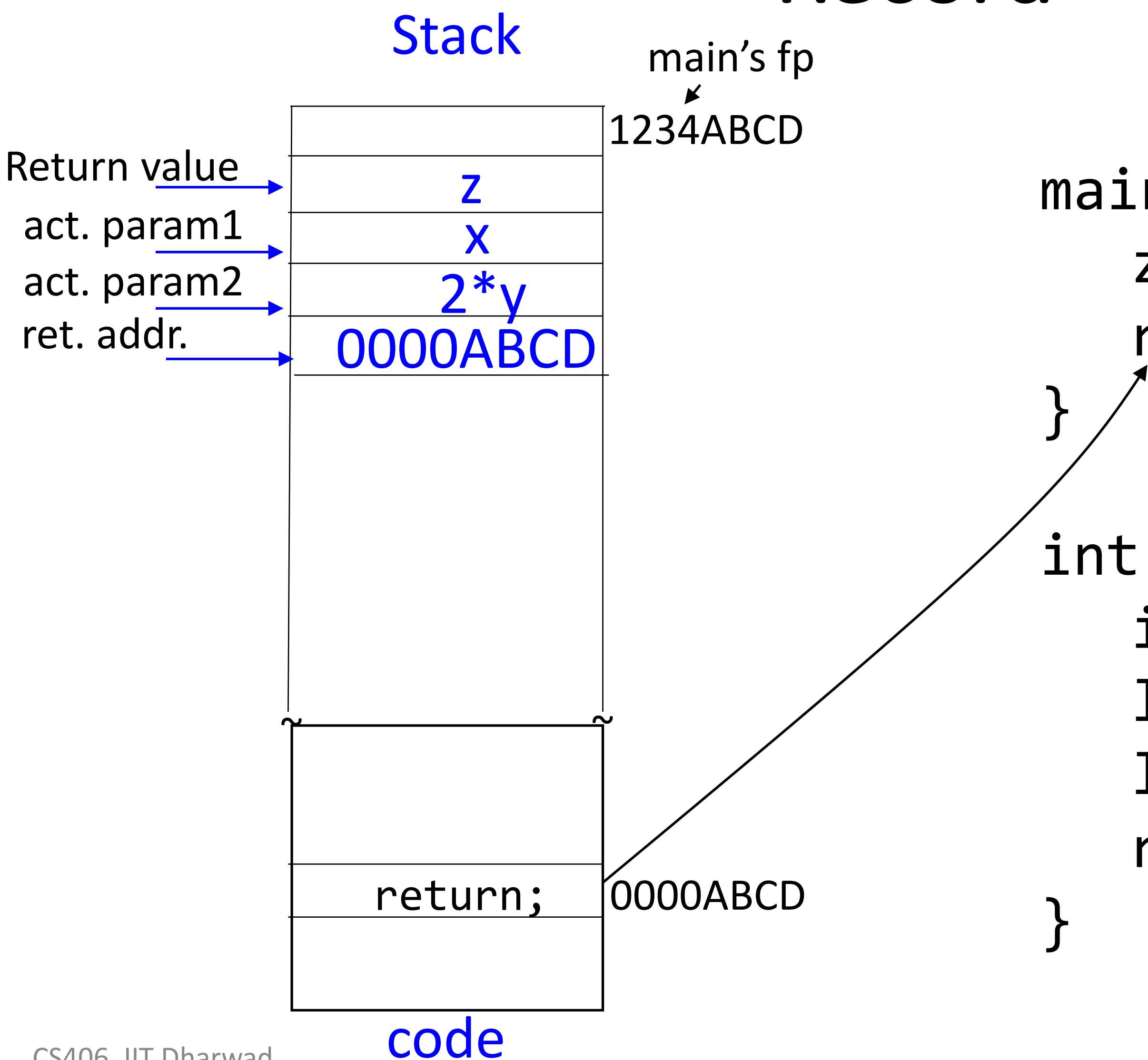
Function call: Peeking at Activation Record




```
main() {
   z=foo(x, 2*y);
   return;
}

int foo(int a, int b) {
   int l1, l2
   l1=a;
   l2=b;
   return l1+l2;
}
```

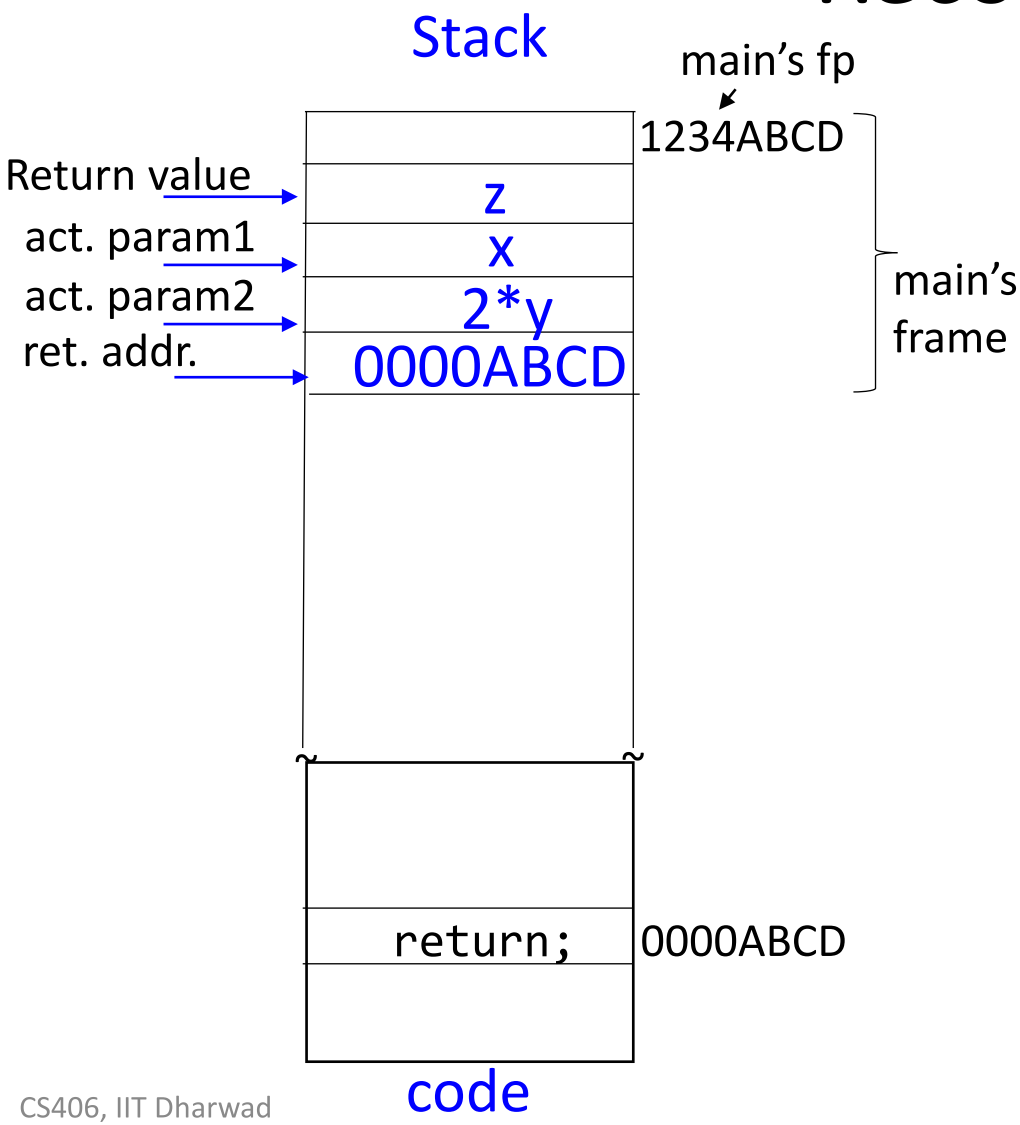
Function call: Peeking at Activation Record




```
main() {
   z=foo(x, 2*y);
   return;
}

int foo(int a, int b) {
   int l1, l2
   l1=a;
   l2=b;
   return l1+l2;
}
```

Function call: Peeking at Activation Record




```
main() {
   z=foo(x, 2*y);
   return;
}

int foo(int a, int b) {
   int l1, l2
   l1=a;
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   return l1+l2;
}
```
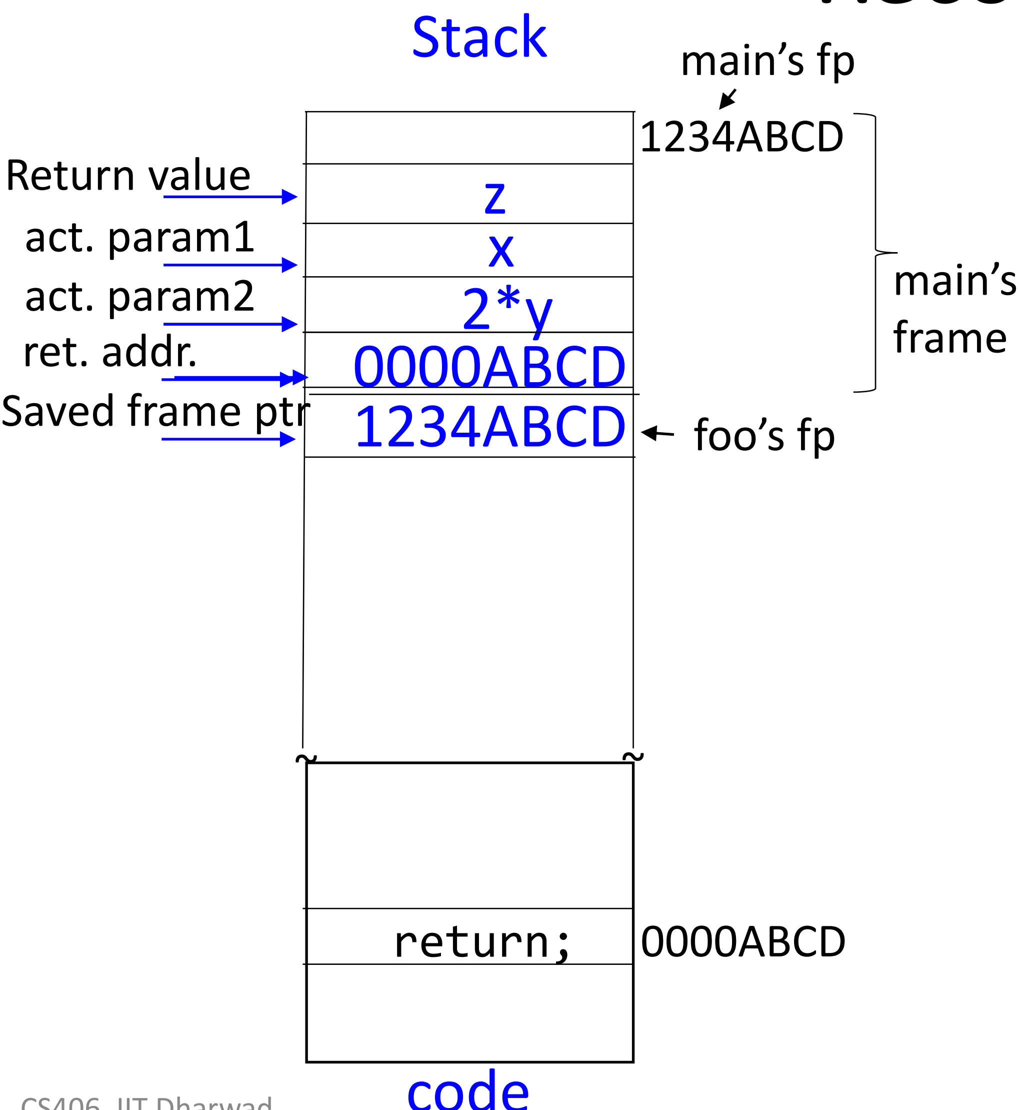
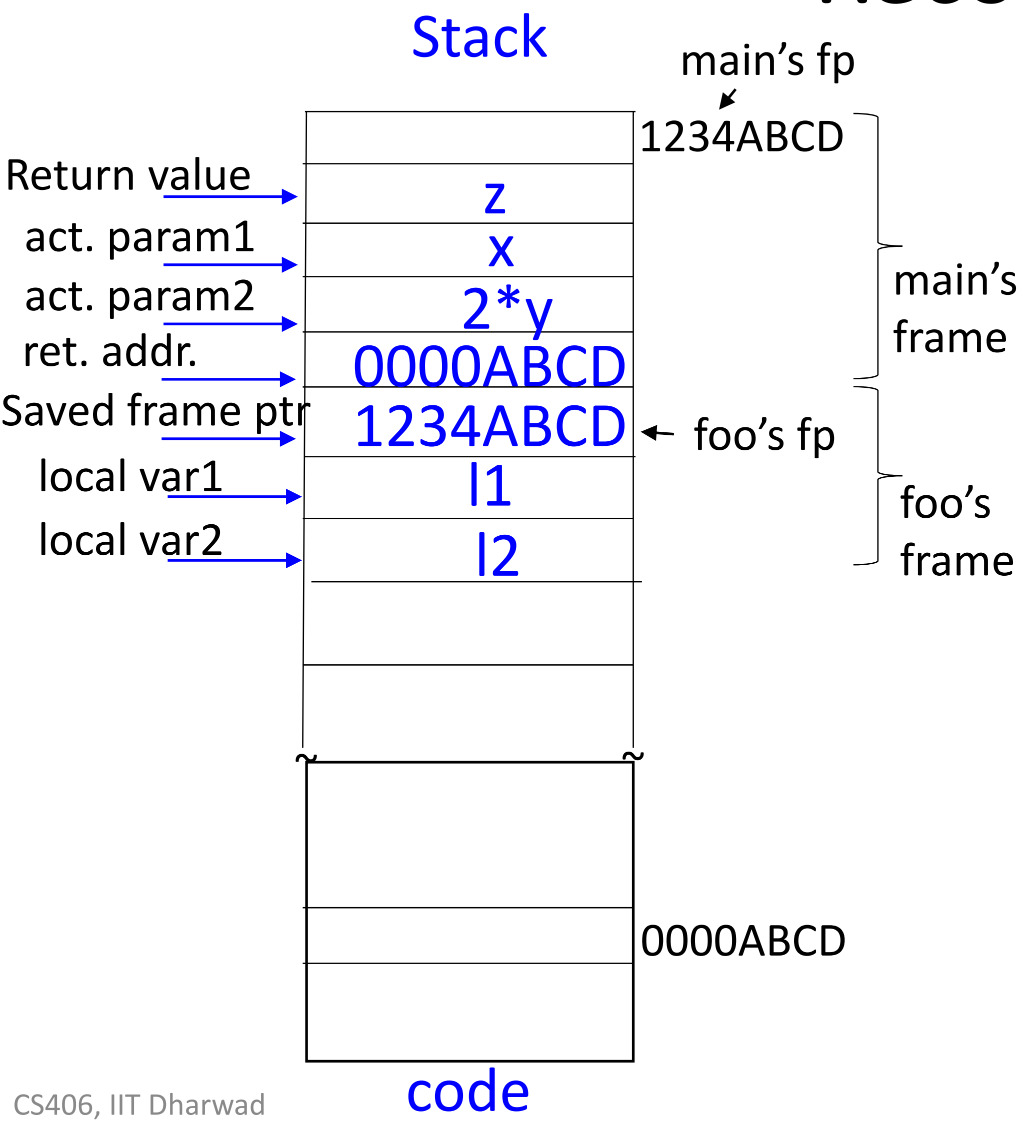

Function call: Peeking at Activation Record




```
main() {
   z=foo(x, 2*y);
   return;
}

int foo(int a, int b) {
   int l1, l2
   l1=a;
   l2=b;
   return l1+l2;
}
```

Function call: Peeking at Activation Record




```
main() {
    z=foo(x, 2*y);
    return;
}

int foo(int a, int b) {
    int l1, l2
    l1=a;
    l2=b;
    return l1+l2;
}
```

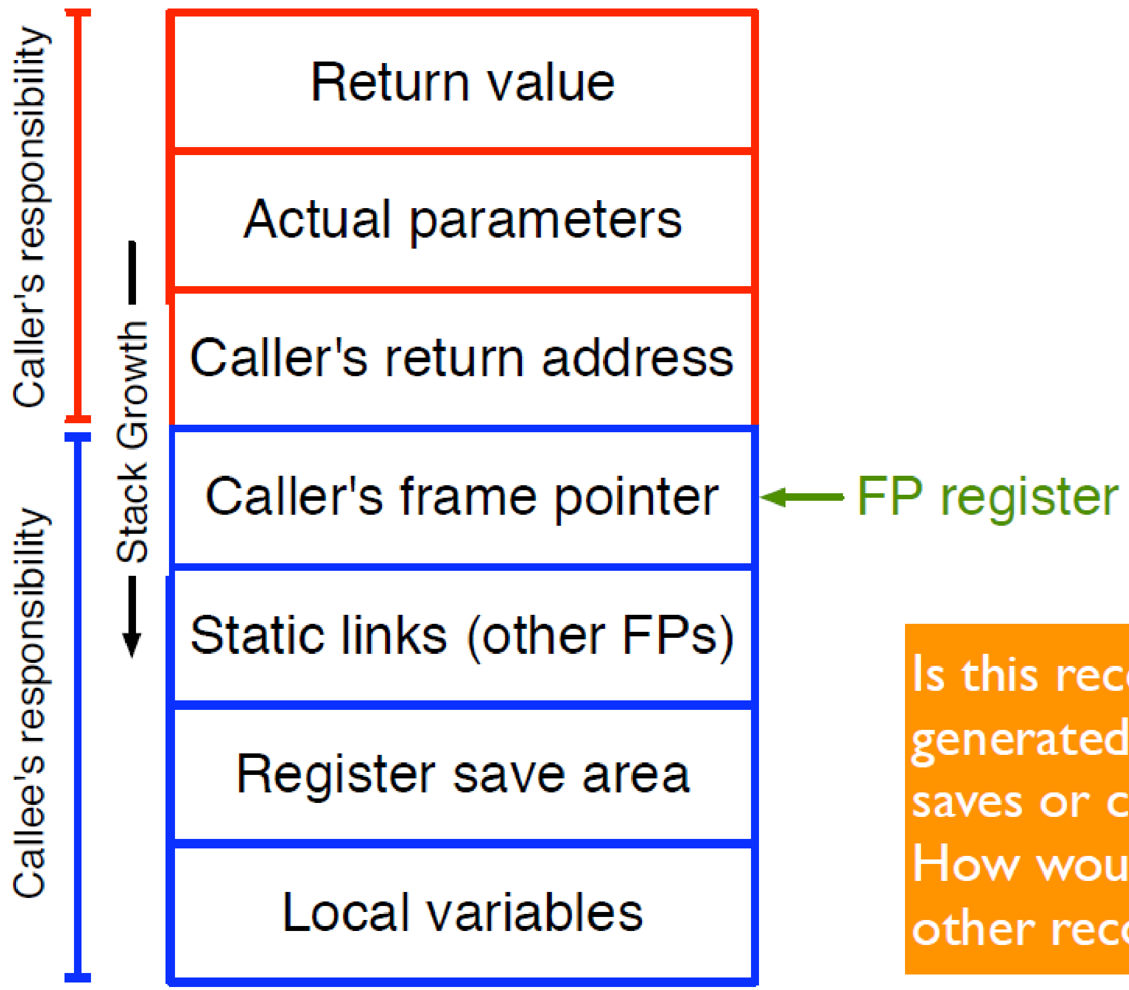
Function calls – Register Handling

- **Did not use registers** in the previous example (for parameter passing)
- Registers are faster than memory. So, compiler should keep parameters in registers whenever possible
- Modern calling convention places first few arguments in registers (arg1 in r1, arg2 in r2, arg3 in r3…) and the remaining in memory.
  - In x86 C-ABI, first 6 arguments are passed in registers
- What if callee wants to use registers r1, r2, r3 etc. for local computation? Callee must save the registers in its stack frame.

Function calls – Register Handling

- Two options: caller saves or callee saves
- Caller Saves
  - Caller pushes all the registers it is using on to the stack before calling the function
  - Restores the registers after the function returns
- Callee Saves
  - Callee pushes all the registers it is *going to use* on the stack immediately after being called
  - Restores the registers just before it returns

Activation records



Is this record generated for callee-saves or caller-saves? How would the other record look?

Activation Record – Return Address and Return Value

- Callee must be able to return to the caller when done
- Return address is the address of the instruction following the function call
- Return address can be placed on the stack or on register
- The `call` instruction on modern machines places the return address in a specific register
- Return value is placed in a specific register by the callee function

The frame pointer

- Manipulate with instructions like `link` and `unlink`
  - Link: push current value of FP on to stack, set FP to top of stack
  - Unlink: read value at current address pointed to by FP, set FP to point to that value
  - In other words: link pushes a new frame onto the stack, unlink pops it off

Stack Pointer

- SP is manipulated through push and pop instructions

```
Push x:
stack_pointer--
Memory[stack_pointer] = x


Pop x:
x = Memory[stack_pointer]
stack_pointer--
```

Example Subroutine Call and Stack Frame

	return value
	x
	2*y
	return address
R6	saved frame ptr
	l1
	l2
	. . .

stack

Lower addr

```
z = SubOne(x,2*y);
```

```
int SubOne(int a, int b) {
     int l1, l2;
     l1 = a;
     l2 = b;
     return l1+l2;
  };
```

3-address code:

```
push
push x
mul  2  y  t1
push t1
jsr SubOne
pop
pop
pop  z
```

```
link  3
move $P1 $L1
move $P2 $L2
add $L1 $L2 t2
move t2 $R
unlink
ret
```

assembly code:

```
push
push x
load  y R1
muli  2 R1
push R1
jsr SubOne
pop
pop
pop  R1
store R1 z
```

```
link R6 3
load  3(R6)  R1
store R1 -1(R6)
load  2(R6)  R2
store R2 -2(R6)
load  -1(R6)  R1
add   -2(R6)  R1
store R1  4(R6)
unlink
```

Question ?

Where are the command-line arguments stored?

How about environment variables such as LD_LIBRARY_PATH and PATH?

Challenge Q: *are there scenarios where the activation record is required to be allocated on the heap?*

```
fun f(x) =
let
    fun g(y) = x + y
in
    g
end


val z = f(4)
val w = z(5)
```

Local Optimizations

Naïve approach

- "Macro-expansion"
  - Treat each 3AC instruction separately, generate code in isolation

```
ADD A, B, C   →   LD A, R1
                  LD B, R2
                  ADD R1, R2, R3
                  ST R3, C

MUL A, 4, B   →   LD A, R1
                  MOV 4, R2
                  MUL R1, R2, R3
                  ST R3, B
```

Why is this bad? (I)

MUL A, 4, B →

LD A, R1
MOV 4, R2
MUL R1, R2, R3
ST R3, B

MUL A, 4, B →

LD A, R1
MULI R1, 4, R3
ST R3, B

There is a better instruction available!

Too many instructions
Should use a different instruction type

Why is this bad? (II)

ADD A, B, C

LD A, R1
LD B, R2
ADD R1, R2, R3
ST R3, C

ADD C, A, E

LD C R4

This LD is redundant

LD A R5

This LD is redundant

ADD R4 R5 R6

ST R6 E

Why is this bad? (III)

ADD A, B, C	LD A, R1
	LD B, R2
	ADD R1, R2, R3
	ST R3, C

ADD A, B, C
ADD A, B, D
	LD A, R1
	LD B, R2
	ADD R1, R2, R3
	ST R3, C
	LD A, R4
	LD B, R5
	ADD R4, R5, R6
	ST R6, D

Wasting instructions recomputing A + B

How do we address this?

- Several techniques to improve performance of generated code
  - *Instruction selection* to choose better instructions
  - *Peephole optimizations* to remove redundant instructions
  - *Common subexpression elimination* to remove redundant computation
  - *Register allocation* to reduce number of registers used

Instruction selection

- Even a simple instruction may have a large set of possible address modes and combinations

+ A B C

- C: Can be indirect, register, memory address, indexed, etc.
- B: Can be literal, register, memory address, indexed, etc.
- A: Can be literal, register, memory address, indexed, etc.

- Dozens of potential combinations!

More choices for instructions

- Auto increment/decrement (especially common in embedded processors as in DSPs)
  - e.g., load from this address and increment it
  - Why is this useful?
- Three-address instructions
- Specialized registers (condition registers, floating point registers, etc.)
- "Free" addition in indexed mode

  MOV (R1)offset R2

  - Why is this useful?

Peephole optimizations

- Simple optimizations that can be performed by pattern matching
  - Intuitively, look through a "peephole" at a small segment of code and replace it with something better
  - Example: if code generator sees `ST R X; LD X R`, eliminate load
- Can recognize sequences of instructions that can be performed by single instructions

  `LDI R1 R2; ADD R1 4 R1` replaced by

  `LDINC R1 R2 4` //load from address in R1 then inc by 4

Peephole optimizations

- Simple optimizations that can be performed by pattern matching
  - Intuitively, look through a "peephole" at a small segment of code and replace it with something better
  - Example: if code generator sees `ST R X; LD X R`, eliminate load

Get the data present at address in R2 and put it in R1

be

`LDI R1 R2; ADD R1 4 R1` replaced by

`LDINC R1 R2 4` //load from address in R1 then inc by 4

Peephole optimizations

- Constant folding

```
ADD lit1, lit2, Rx → MOV lit1 + lit2, Rx
MOV lit1, Rx
ADD li2, Rx, Ry    → MOV lit1 + lit2, Ry
```

- Strength reduction

```
MUL operand, 2, Rx → SHIFTL operand, 1, Rx
DIV operand, 4, Rx → SHIFTR operand, 2, Rx
```

- Null sequences

```
MUL operand, 1, Rx → MOV operand, Rx
ADD operand, 0, Rx → MOV operand, Rx
```

Peephole optimizations

- Combine operations

```
JEQ L1
JMP L2          →  JNE L2
L1: ...
```

- Simplifying

```
SUB operand, 0, Rx  →  NEG Rx
```

- Special cases (taking advantage of ++/--)

```
ADD 1, Rx, Rx   →  INC Rx
SUB Rx, 1, Rx   →  DEC Rx
```

- Address mode operations

```
MOV A R1
ADD 0(R1) R2 R3  →  ADD @A R2 R3
```

Superoptimization

- Peephole optimization/instruction selection writ large
- Given a sequence of instructions, find a different sequence of instructions that performs the same computation in less time
- Huge body of research, pulling in ideas from all across computer science
    - Theorem proving
    - Machine learning

Common subexpression elimination

- Goal: remove redundant computation, don't calculate the same expression multiple times

1: A = B * C

2: E = B * C

Keep the result of statement 1 in a temporary and reuse for statement 2

- Difficulty: how do we know when the same expression will produce the same result?

1: A = B * C

2: B = <new value>

3: E = B * C

B is "killed." Any expression using B is no longer "available," so we cannot reuse the result of statement 1 for statement 3

- This becomes harder with pointers (how do we know when B is killed?)