COS 217: Introduction to Programming Systems

Assembly Language

Local Variables and Function Calls



PRINCETON UNIVERSITY

This Lecture



We've learned several things in lecture and precept:

- Arithmetic and logic operations
- Data Structures (including with indirection)
- Control flow: GOTO a new location and resume executing there

Function calls are more complex:

- Have to go and also come back: more complex control flow
- Functions can call other functions before they return: how to manage state

Goal: Learn how function calls are implemented in AARCH64

- Learn how indirection, abstraction, and data structures are used

Problems to Solve in Function Calls



(1) Control flow: Calling and returning
- How does caller function jump to callee function?
- How does callee function jump back to correct place in caller function?

(2) Passing arguments
- How does caller function pass arguments to callee function?

(3) Storing local variables
- Where does callee function store its local variables?

(4) Returning a value
- How does callee function return a value back to caller function?
- How does caller function access the return value?

(5) Optimization
- How do caller and callee function minimize memory accesses?

Running Example

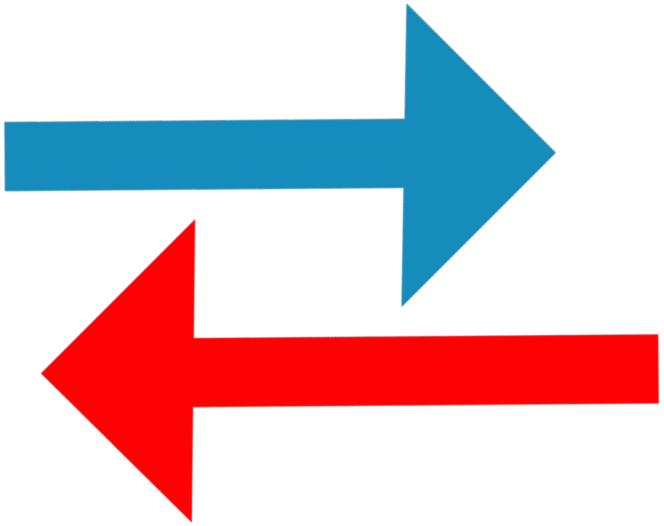


```
long absadd(long a, long b)
{
    long absA, absB, sum;
    absA = labs(a);
    absB = labs(b);
    sum = absA + absB;
    return sum;
}
```

`absadd()` calls C `labs()` function, which returns absolute value of given long

Uses local variables, calls functions with parameters

Let's start with the basics of calling and returning



CALLING AND RETURNING

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Problem 1: Calling and Returning

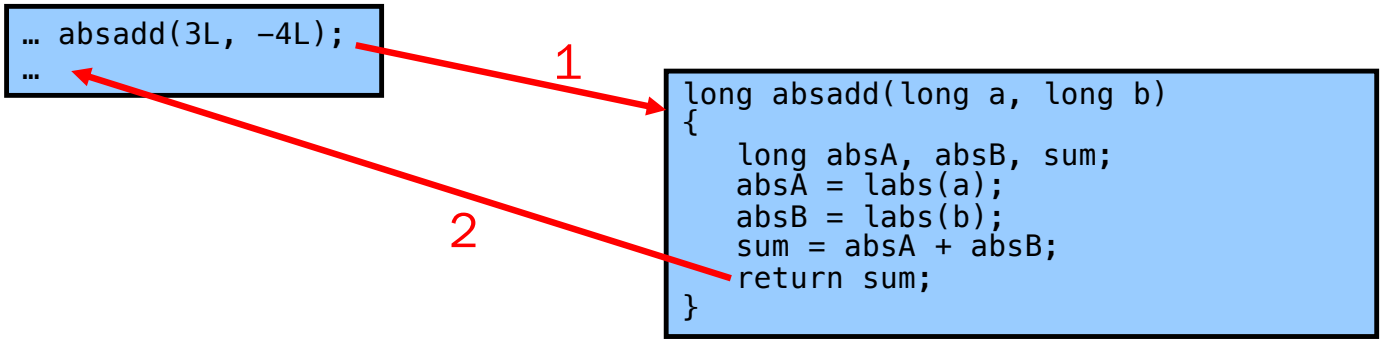


How does caller call the callee?

i.e., jump to (goto) the address of the callee's first instruction

How does callee get back to the right place in the caller?

i.e., jump to the instruction immediately following the most-recently-executed call

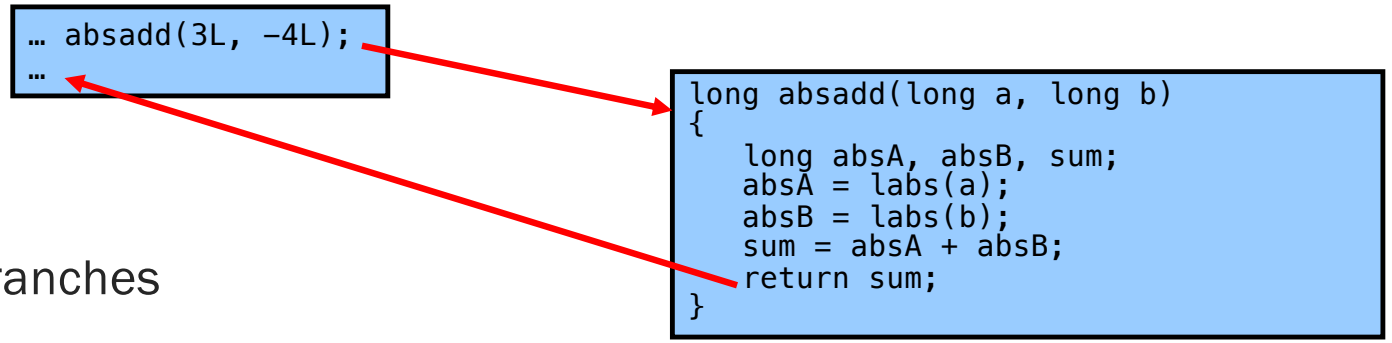




iClicker Question



Q: What instructions would we use to “jump” into and back out of the callee?



A. 2 conditional branches

B. 1 conditional branch, then 1 unconditional branch

C. 1 unconditional branch, then 1 conditional branch

D. 2 unconditional branches

E. Something more complicated

Attempted Solution: b Instruction



Caller and callee use b (unconditional branch) instruction and text section labels

```
f:
   …
   b g      // Call g
fReturnPoint:
   …
```

```
g:
   …
   b fReturnPoint     // Return
```

Attempted Solution: b Instruction



Problem: callee may be called by multiple callers

```
f:
   …
   b g      // Call g
fReturnPoint:
   …
```

```
g:
   …
   b ???      // Return
```

```
h:
   …
   b g      // Call g
hReturnPoint:
   …
```

Partial Solution: Indirection



Put return address in a register. Value changes based on where it's called from

`br` (branch register) instruction branches to address in X register operand

```
f1:
   adr x30, f1ReturnPoint
   b g          // Call g
f1ReturnPoint:
   …
```

```
f2:
   adr x30, f2ReturnPoint
   b g          // Call g
f2ReturnPoint:
   …
```

```
g:
   …
   br x30       // Return
```

Correctly returns to either `f1` or `f2`

`adr` instruction before every function call

Label after every function call

Caller and callee must use same register

Partial Solution: Abstraction



`bl` (branch and link) instruction stores return point in X30

`ret` (return) instruction returns to address in X30, and it's always X30 (in hardware)

```
f1:
   bl g        // Call g
   …
```

```
f2:
   bl g        // Call g
   …
```

```
g:
   …
   ret         // Return
```

Correctly returns to either `f1` or `f2`

Takes care of the three things on previous slide under the hood

Aside: so `ret` is identical to `b x30`, right? Yes and no …
https://www.mattkeeter.com/blog/2023-01-25-branch/

Not quite there yet …



Problem: Cannot handle nested function calls

```
f:
   bl g        // Call g
   ...         // location 1
```

```
g:
   bl h        // Call h
   ...         // location 2
   ret         // Return
```

Problem if f( ) calls g( )
then g( ) calls h( )

X30 starts at loc 1 in f but overwritten by loc 2 in g

Return address g( ) → f( ) is lost
g( ) returns to the middle of g( ) …

```
h:
   ... ... ...
   ret         // Return
```

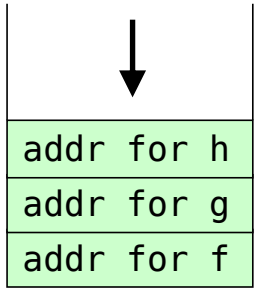
Register is not enough. Need to save a function's return address somewhere when other functions it has called are running, and restore to the register when it runs again

How Do We Keep Track of Calls and Returns?



Need an elegant way to save and restore return addresses. Observations:

- Every function call needs **separate** tracking of a return address
  - A function I call will overwrite X30 (return address), so I better save it somewhere
  - My return address must be saved for as long as I am live, then discarded
  - Nested function calls means a lot of return addresses to save: no. not known in advance
- ***Key: Stored return addresses are discarded in reverse order of creation***
  - `f()` calls `g()` ⇒ return addr for `f` is stored
  - `g()` calls `h()` ⇒ return addr for `g` is stored
  - `h()` returns to `g()` ⇒ return addr for `g` is discarded
  - `g()` returns to `f()` ⇒ return addr for `f` is discarded



- ***This is true for any call-return pattern***. So LIFO data structure (***stack***) is appropriate
- When a function returns, all functions it has called (nested) must have returned, so it is at top

Same idea as stackframes for temp space for C programs. In fact, we'll put more than the return address on the stack. But let's stick to return address first

Saving Link (Return) Addresses



Push X30 on stack when entering a function
Pop X30 from stack before returning from a function

```
f:
   // Save X30
   ...
   bl g // Call g
   ...
   // Restore X30
   ret
```

```
g:
   // Save X30
   ...
   bl h // Call h
   ...
   // Restore X30
   ret
```

```
h:
   ...
   ret
```

Stack Operations

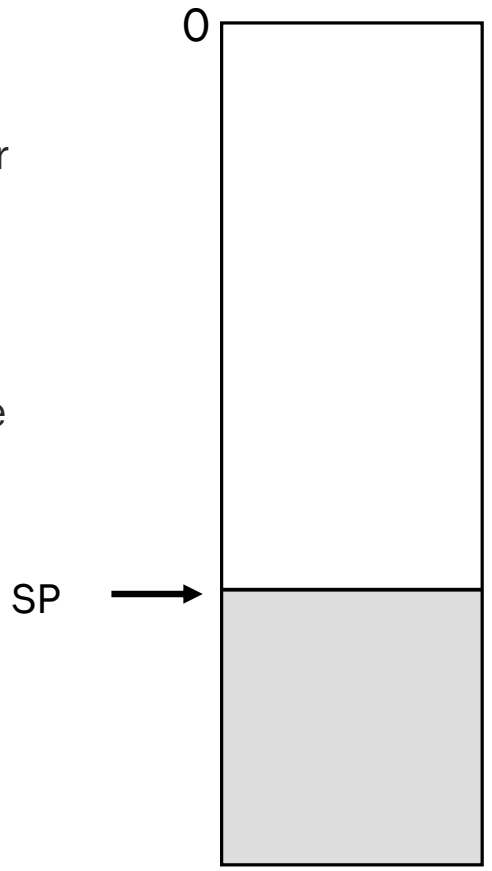


SP (stack pointer) register points to top of stack

- Points to beginning of active stack frame, i.e. stack frame for currently active function, as that is at the top
- If active function calls a function, latter's stack frame will be pushed above this point and SP moved to its top
- Etc.
- It's global: at any given time, points to top active stack frame

SP

- can be used in `ldr` and `str` instructions
- can be used in arithmetic instructions
- must be multiple of 16, in AARCH64



Stack Operations

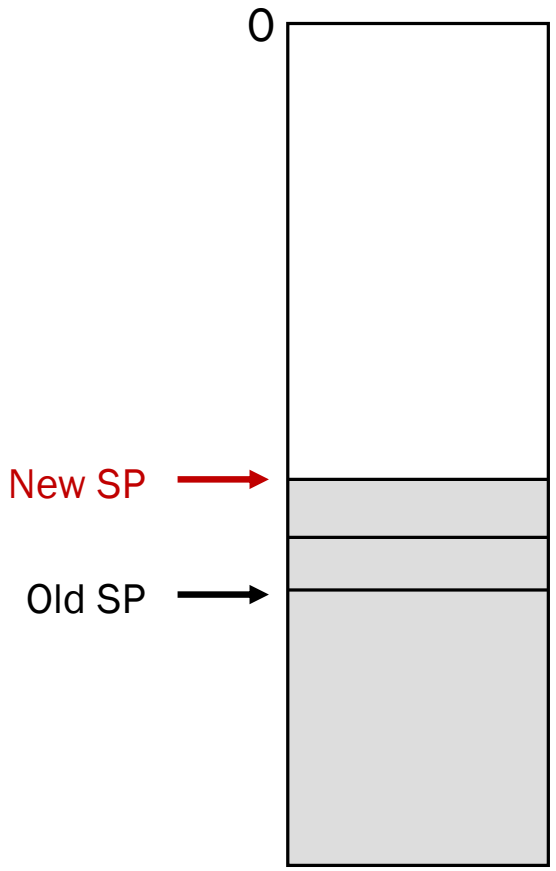


To create (push) new stack frame at top of stack (when this function is called and becomes active):

- Decrement `sp`

```
sub sp, sp, 16
```

- 16 is the minimum size allowed, even if all is being stored is the return value of 8 bytes
  - Be careful about this: the error message is not helpful

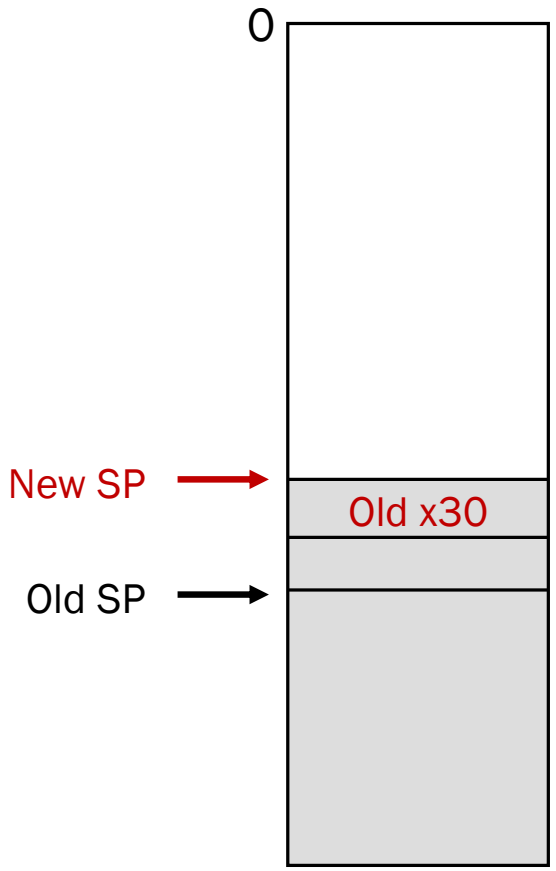


Stack Operations

Stack is in memory, so can load/store information from and to it:

- Load/store X30 value at or offset from `sp`

```
str x30, [sp]
…
ldr x30, [sp]
```



Stack Operations

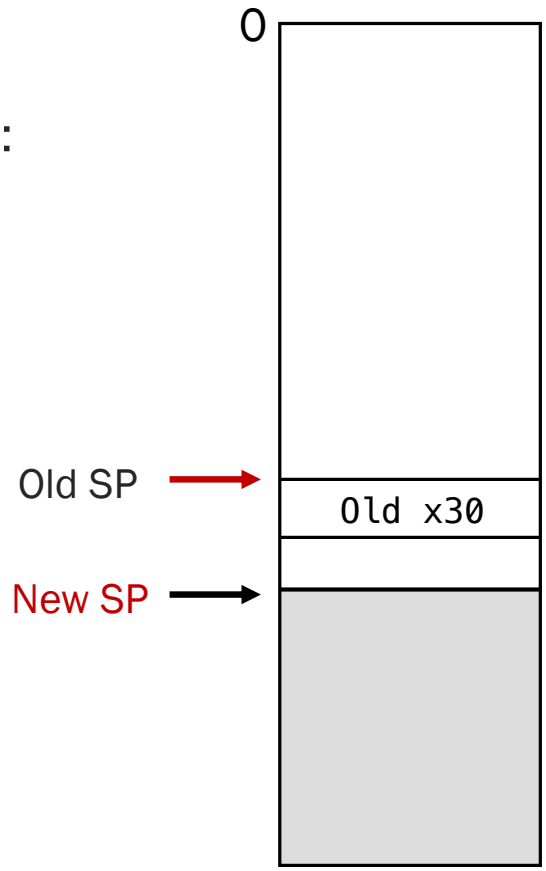


To delete (pop) the current active stack frame (when this function returns and becomes inactive):

- Increment `sp`

```
add sp, sp, 16
```

- Assumes size of frame is 16 bytes
  - Could be much bigger, of course
- Must first restore value of X30 from stack to X30 register, since X30's value may have changed if we made function calls. Don't want the value lost when this stack frame goes away
- (Note: data above New SP are not erased, just stay there. But no longer valid program data.)



So, Function Call Prolog and Epilog …



Prolog: Make room on stack; Push X30 (ret address). Then execute function code
Epilog: Pop X30 from stack; tear down stack frame. Then return from function

```
f:
   // Save X30
   sub sp, sp, 16
   str x30, [sp]
   ...
   bl g  # Call g
   ...
   // Restore X30
   ldr x30, [sp]
   add sp, sp, 16
   ret
```

```
// this will change X30 value,
// which is why it was saved
// on stack

// before f returns, its ret
// address needs to be in X30
// so must be restored from
// stack before ret instruction
```

```
g:
   // Save X30
   sub sp, sp, 16
   str x30, [sp]
   ...
   bl h  # Call h
   ...
   // Restore X30
   ldr x30, [sp]
   add sp, sp, 16
   ret
```

```
h:
   ...
   ret
```

Running Example



```
long absadd(long a, long b)
{
    long absA, absB, sum;
    absA = labs(a);
    absB = labs(b);
    sum = absA + absB;
    return sum;
}
```

Can now manage return addresses across calls/returns

- What about arguments, like a and b?
- What about local variables, like absA and absB?
- What about return values, like sum?

Key: all live as long function invocation hasn't returned, and must be saved from functions called during that time

Use the stack for these as well

- Beautiful, elegant solution to all these problems
- Then we'll make things uglier by optimizing for performance

```
// long absadd(long a, long b)
absadd:
    sub sp, sp, 16
    str x30, [sp]
    // long absA, absB, sum
    ...
    // absA = labs(a)
    ...
    bl labs
    ...
    // absB = labs(b)
    ...
    bl labs
    ...
    // sum = absA + absB
    ...
    // return sum
    ...
    ldr x30, [sp]
    add sp, sp, 16
    ret
```



PASSING ARGUMENTS

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Problem 2: Passing Arguments



Problem:

- How does caller pass arguments to callee?
- How does callee accept parameters from caller?

```
long absadd(long a, long b)
{
    long absA, absB, sum;
    absA = labs(a);
    absB = labs(b);
    sum = absA + absB;
    return sum;
}
```

ARM Solution 1: Use the Stack



A realization of our understanding from C that these go on the stack

Observations (déjà vu):

- Would like to store in registers for performance, but limited no. of registers
- May need to store many argument sets
  - The number of argument sets is not known in advance
  - If this function calls any others, the argument set must be saved for as long as the invocation of this function is live, and discarded thereafter
- *Stored argument sets are destroyed in reverse order of creation*
- *LIFO data structure (stack) is appropriate*

ARM Solution 2: Use Registers



AARCH64 solution:

- Pass first 8 (integer or address) arguments in registers for efficiency
  - X0..X7 and/or W0..W7
- More than 8 arguments ⇒ Pass arguments 9, 10, … on the stack
  - (Beyond scope of COS 217)
- Arguments are structures ⇒ Pass arguments on the stack
  - (Beyond scope of COS 217)

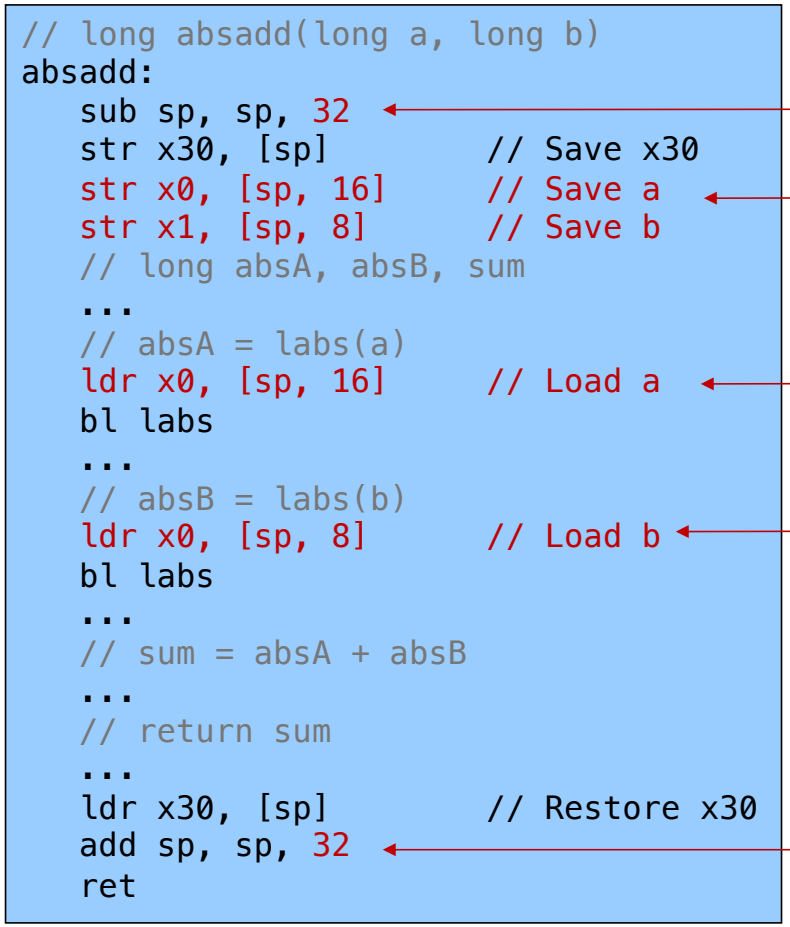
Callee function then may save those registers X0..X7 to the stack

- Since function calls it makes will use X0..X7 the same way and may destroy values; or its own code may overwrite X0..X7 and the incoming argument values will be lost

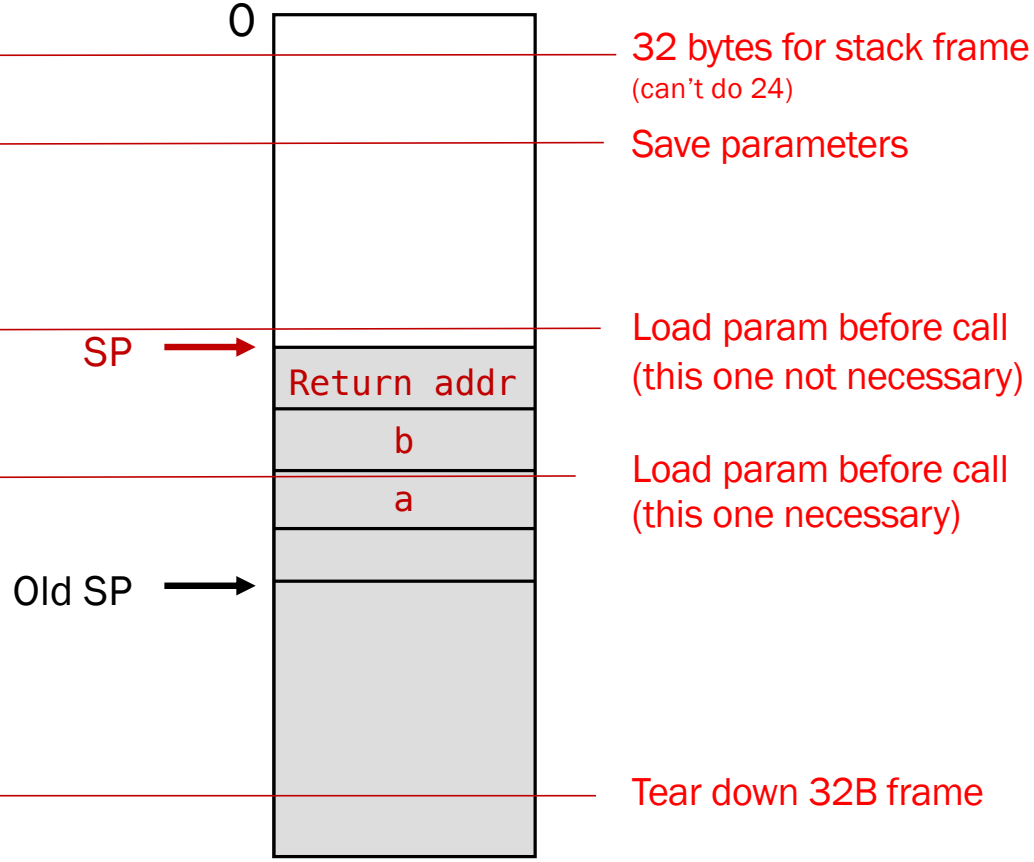
Then, it can reference arguments as offsets from `sp`, as with return value (at `sp`)

Or maybe not (See “optimization” later this lecture)

Running Example



```
// long absadd(long a, long b)
absadd:
   sub sp, sp, 32
   str x30, [sp]          // Save x30
   str x0, [sp, 16]       // Save a
   str x1, [sp, 8]        // Save b
   // long absA, absB, sum
   ...
   // absA = labs(a)
   ldr x0, [sp, 16]       // Load a
   bl labs
   ...
   // absB = labs(b)
   ldr x0, [sp, 8]        // Load b
   bl labs
   ...
   // sum = absA + absB
   ...
   // return sum
   ...
   ldr x30, [sp]          // Restore x30
   add sp, sp, 32
   ret
```





STORING LOCAL VARIABLES

Problem 3: Storing Local Variables



Where does callee function store its local variables?

```
long absadd(long a, long b)
{
    long absA, absB, sum;
    absA = labs(a);
    absB = labs(b);
    sum = absA + absB;
    return sum;
}
```

In C, we say they're on the stack. But where are they really in ARM?

ARM Solution: Use the Stack



Observations (this is getting repetitive …):

- Would like to store in registers for performance, but finite no. or registers
- May need to store many local variable sets
  - The number of local variable sets is not known in advance
  - Local variable sets must be saved
    for as long as the invocation of this function is live, and discarded thereafter
- Stored local variable sets are destroyed in reverse order of creation
- LIFO data structure (stack) is appropriate

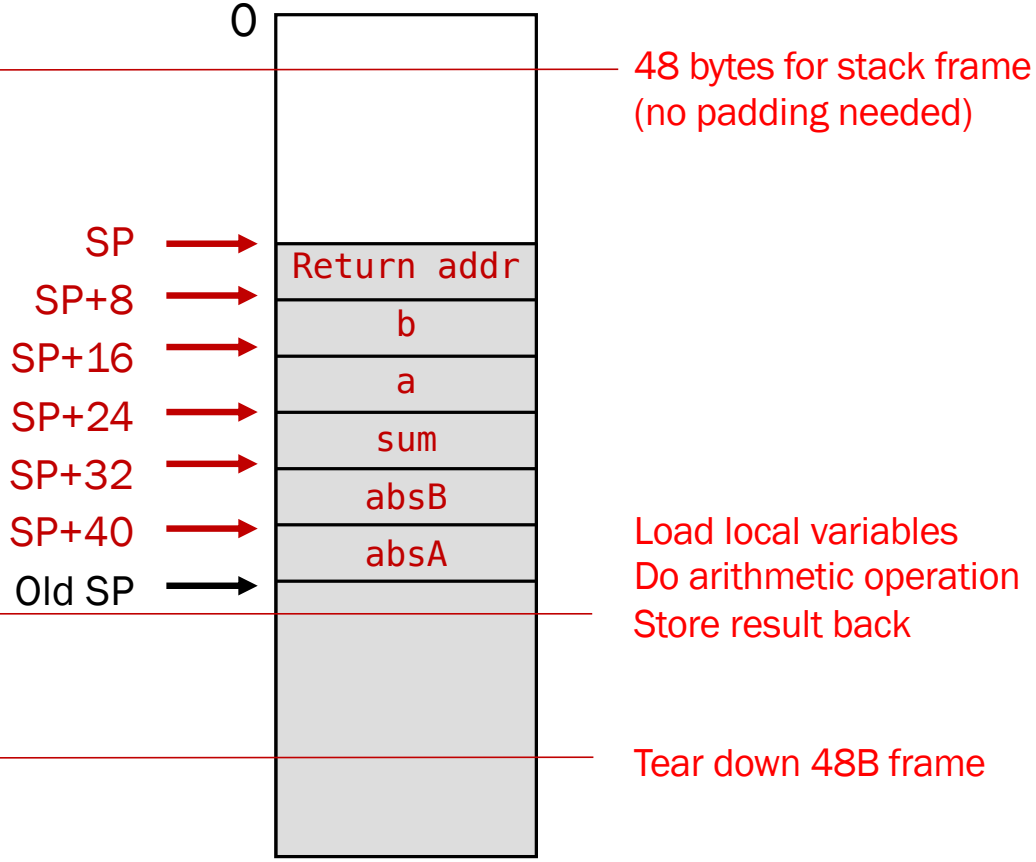
AARCH64 solution:

- Use the STACK section of memory
- Or maybe not (see later this lecture)

Running Example



```
// long absadd(long a, long b)
absadd:
   // long absA, absB, sum
   sub sp, sp, 48
   str x30, [sp]      // Save x30
   str x0, [sp, 16]   // Save a
   str x1, [sp, 8]    // Save b
   // absA = labs(a)
   ldr x0, [sp, 16]   // Load a
   bl labs
   ...
   // absB = labs(b)
   ldr x0, [sp, 8]    // Load b
   bl labs
   ...
   // sum = absA + absB
   ldr x0, [sp, 40]   // Load absA
   ldr x1, [sp, 32]   // Load absB
   add x0, x0, x1
   str x0, [sp, 24]   // Store sum
   // return sum
   ...
   ldr x30, [sp]      // Restore x30
   add sp, sp, 48
   ret
```





RETURNING A VALUE

Problem 4: Return Values



Problem:

- How does callee function send return value back to caller function?
- How does caller function access return value?

```
long absadd(long a, long b)
{
    long absA, absB, sum;
    absA = labs(a);
    absB = labs(b);
    sum = absA + absB;
    return sum;
}
```

ARM Solution: Use X0 / W0



In principle

- Like return address, store return value in stack frame of caller (so caller always has it)
- Caller allocates space in its stack frame for the return value

Or, for efficiency, recognize return value is set just before return and used just after

- Known small size ⇒ store return value in register
- For unknown or large size ⇒ still store return value in stack frame of caller

AARCH64 convention

- Integer or address ⇒ Store return value in X0 / W0
- Floating-point number ⇒ Store return value in floating-point register (Beyond scope of COS 217)
- Structure ⇒ Store return value in memory pointed to by X8. (Beyond scope of COS 217)

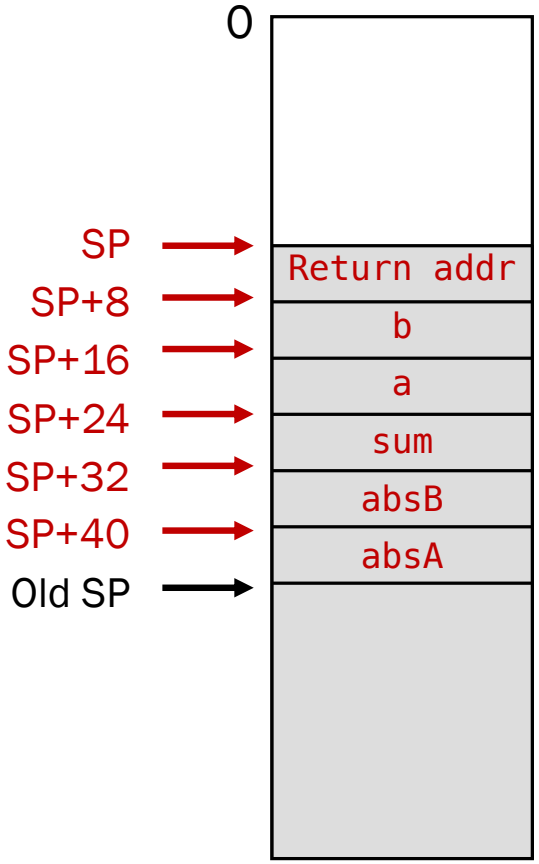
In our example, return value can be stored to the local variable on stack, e.g. `absA`

```
absA = labs(a);  // labs(a) returns it in x0, str it from there
```

Running Example



```
// long absadd(long a, long b)
absadd:
   // long absA, absB, sum
   sub sp, sp, 48
   str x30, [sp]      // Save x30
   str x0, [sp, 16]   // Save a
   str x1, [sp, 8]    // Save b
   // absA = labs(a)
   ldr x0, [sp, 16]   // Load a
   bl labs
   str x0, [sp, 40]   // Store absA
   // absB = labs(b)
   ldr x0, [sp, 8]    // Load b
   bl labs
   str x0, [sp, 32]   // Store absB
   // sum = absA + absB
   ldr x0, [sp, 40]   // Load absA
   ldr x1, [sp, 32]   // Load absB
   add x0, x0, x1
   str x0, [sp, 24]   // Store sum
   // return sum
   ldr x0, [sp, 24]   // Load sum
   ldr x30, [sp]      // Restore x30
   add sp, sp, 48
   ret
```



Are We Done?



Program works, and follows the idiom

We've come a long way

But not optimized for performance

- Look even at what we last did:

```
add x0, x0, x1
str x0, [sp, 24]  // Store sum
// return sum
ldr x0, [sp, 24]  // Load sum
ldr x30, [sp]     // Restore x30
add sp, sp, 48
ret
```



OPTIMIZATION

(More to come on this general topic in a later lecture)

Optimization: Using Registers More Than the Stack



Observation: Accessing memory is expensive

- Orders of magnitude more expensive than accessing registers. Stack is in main memory
- For efficiency, want to store and reuse parameters and local variables in registers if possible
- So far: `ldr` from stack, use once, `str` to stack. Want to reduce use of stack, use registers instead

Observation: Registers are a finite resource (same problem that led us to use stack)

- Desired Abstraction: Every function has its own registers
- In reality: All functions share same small set of registers

Problem: How do caller and callee use the same set of registers without interference?

- Callee may use register that the caller also is using
- When callee returns control to caller, old register contents may have been lost
- Caller function cannot continue where it left off

Solution: carve off some registers for which you're guaranteed any function you call won't corrupt them; for others, don't assume that

ARM Solution: Register Conventions



Callee-saved registers (callee will ensure values aren't corrupted)

- X19..X29 (or W19..W29). All callees ensure preservation of values, so safe
- Callee function must preserve contents or restore them before returning
  - **Caller doesn't have to save registers before calling callee**
- If necessary (e.g. if callee or its callees may modify these registers) …
  - Callee saves caller's register values to stack near beginning
  - Callee restores caller's register values from stack near end
  - Caller is also someone's callee, so may need to do this. So, savings vary

ARM Solution: Register Conventions



Callee-saved registers (callee must ensure values aren't corrupted)

- X19..X29 (or W19..W29). All callees ensure preservation of values, so safe
- Callee function must preserve contents or restore them before returning
  - **Caller doesn't have to save registers before calling callee**
- If necessary (e.g. if callee or its callees may modify these registers) …
  - Callee saves caller's register values to stack near beginning
  - Callee restores caller's register values from stack near end
  - Caller is also someone's callee, so may need to do this. So, savings vary

Caller-saved registers (caller's job to ensure values aren't corrupted)

- X8..X18 (or W8..W18) – plus parameters in X0..X7
- Callee can change contents and doesn't have to restore them, so good for it
- If necessary…
  - Caller saves to stack before call
  - Caller restores from stack after call

Running Example



Parameter handling in unoptimized version:

- `absadd()` accepts parameters (`a` and `b`) in X0 and X1
- At beginning, `absadd()` copies contents of X0 and X1 to stack
- Body of `absadd()` uses stack: loads the values back into registers before each use (call to `bl`)
- At end, `absadd()` pops parameters from stack

Parameter handling in optimized version:

- Idea: if we plan to use the parameters often, keep them in registers rather than only on the stack
- `absadd()` accepts parameters (`a` and `b`) in X0 and X1
- At beginning, copies contents of X0, X1 to callee-saved registers X19, X20, which will remain safe
  - Since callees, like `labs()`, can modify X0 (return value) and X1, which are not callee-saved
- Body of `absadd()` uses X19 and X20, since they are safe from callees
- Must be careful:
  - `absadd()` itself cannot just corrupt contents of X19 and X20, as it is a callee of, say, `main()`
  - So `absadd()` must save X19 and X20 near beginning, and restore near end
  - But it knows every function it calls, and they call, will also ensure the safety of X19 and X20

Running Example



Local variable handling in unoptimized version:

- At beginning, `absadd()` allocates space for local variables (`absA`, `absB`, `sum`) on stack
- Body of `absadd()` uses stack: loads from and stores to variables on stack to use them
- At end, `absadd()` pops local variables from stack

Local variable handling in optimized version:

- `absadd()` keeps local variables in callee-saved registers X21, X22, X23
- Body of `absadd()` uses X21, X22, X23, since they are safe from callees
- Must be careful:
  - `absadd()` cannot just corrupt the contents of X21, X22, X23 as it is a callee of, say, `main()`
  - So `absadd()` must save X21, X22, and X23 near beginning, and restore near end

Note again: we're moving from load-store on every use to load-store once in function

Running Example



```
// long absadd(long a, long b)
absadd:
   // long absA, absB, sum
   sub sp, sp, 48
   str x30, [sp]      // Save x30
   str x19, [sp, 8]   // Save x19, use for a
   str x20, [sp, 16]  // Save x20, use for b
   str x21, [sp, 24]  // Save x21, use for absA
   str x22, [sp, 32]  // Save x22, use for absB
   str x23, [sp, 40]  // Save x23, use for sum
   mov x19, x0        // Save a in x19
   mov x20, x1        // Save b in x20
   // absA = labs(a)
   mov x0, x19        // Prepare to pass a
   bl labs
   mov x21, x0        // Save absA
   // absB = labs(b)
   mov x0, x20        // Prepare to pass b
   bl labs
   mov x22, x0        // Save absB
   // sum = absA + absB
   add x23, x21, x22
   // return sum
   mov x0, x23        // Prepare to return sum
   ldr x30, [sp]      // Restore x30
   ldr x19, [sp, 8]   // Restore x19
   ldr x20, [sp, 16]  // Restore x20
   ldr x21, [sp, 24]  // Restore x21
   ldr x22, [sp, 32]  // Restore x22
   ldr x23, [sp, 40]  // Restore x23
   add sp, sp, 48
   ret
```

`absadd()` stores parameters and local vars in X19..X23, not in memory

`absadd()` cannot destroy contents of X19..X23

So `absadd()` must save X19..X23 near beginning and restore near end

No need to protect anything more before calling `labs()`

Use `mov` rather than `str` to save return values from `labs()`

No stack interaction to set up addition or return value: values are already in registers

Eliminate cases of `str` to stack and soon `ldr` back

Here, we're not reusing the registers very much. Benefits are clearer when we use the registers a lot for computations

Eliminating Redundant Copies



```
// long absadd(long a, long b)
absadd:
   // long absA, absB, sum
   sub sp, sp, 32
   str x30, [sp]      // Save x30
   str x19, [sp, 8]   // Save x19, use for b
   str x20, [sp, 16] // Save x20, use for absA
   mov x19, x1        // Save b in x19
   // absA = labs(a)
   bl labs            // a already in x0
   mov x20, x0        // Save absA
   // absB = labs(b)
   mov x0, x19        // Load b
   bl labs
   // sum = absA + absB
   add x0, x20, x0    // x0 held absB, now holds sum
   // return sum – already in x0
   ldr x30, [sp]      // Restore x30
   ldr x19, [sp, 8]   // Restore x19
   ldr x20, [sp, 16] // Restore x20
   add sp, sp, 32
   ret
```

Further optimization: remove redundant ‘mov’ instructions between registers

- Have to save x30, as we make function calls
- a, in x0, is immediately used in x0 and not again. No need to move to callee-saved reg.
- b, in x1, must survive first labs() call, so must save (in callee-saved reg, here, or on stack)
- After computing absB, can just use x0 for it
- sum can also stay in x0 as ends up there

- “Hybrid” pattern uses caller- and callee-saved
- Can be confusing: no longer a systematic mapping between variables and registers
- Attempt only after you have working code
- Save working versions for easy comparison

Non-Optimized vs. Optimized Patterns



Unoptimized pattern

- Parameters and local variables strictly in memory (stack) during function execution
- Pro: Always possible
- Con: Inefficient
- gcc compiler uses this pattern when invoked without –O option

Optimized pattern

- Parameters and local variables mostly in registers during function execution
- Pro: Efficient
- Con: Sometimes impossible, and can be very error-prone for human beings
  - Too many local variables
  - Local variable is a structure or array
  - Function computes address of parameter or local variable
- gcc compiler uses this pattern when invoked with –O option, when it can



WRITING READABLE CODE

Writing Readable Code



```
// long absadd(long a, long b)
absadd:
   // long absA, absB, sum
   sub sp, sp, 48
   str x30, [sp]
   str x19, [sp, 8]
   str x20, [sp, 16]
   str x21, [sp, 24]
   str x22, [sp, 32]
   str x23, [sp, 40]
   mov x19, x0
   mov x20, x1
   // absA = labs(a)
   mov x0, x19
   bl labs
   mov x21, x0
   // absB = labs(b)
   mov x0, x20
   bl labs
   mov x22, x0
   // sum = absA + absB
   add x23, x21, x22
   // return sum
   mov x0, x23
   ldr x30, [sp]
   ldr x19, [sp, 8]
   ldr x20, [sp, 16]
   ldr x21, [sp, 24]
   ldr x22, [sp, 32]
   ldr x23, [sp, 40]
   add sp, sp, 48
   ret
```

Problem

- Hardcoded sizes, offsets, registers are difficult to read, understand, debug

Writing Readable Code



```
    // Stack frame size in bytes
    .equ STACKSIZE, 48
    // Registers for parameters
    a    .req x19
    b    .req x20
    // Registers for local variables
    absA .req x21
    absB .req x22
    sum  .req x23

// long absadd(long a, long b)
absadd:
    // long absA, absB, sum
    sub sp, sp, STACKSIZE
    str x30, [sp]     // Save x30
    str x19, [sp, 8]  // Save x19
    str x20, [sp, 16] // Save x20
    str x21, [sp, 24] // Save x21
    str x22, [sp, 32] // Save x22
    str x23, [sp, 40] // Save x23
    mov a, x0         // Save a (in x19)
    mov b, x1         // Save b (in x20)

    ...
```

Problem

- Hardcoded sizes, offsets, registers are difficult to read, understand, debug

Using .equ and .req

- To define a symbolic name for a constant:
  `.equ SOMENAME, nnn`

- To define a symbolic name for a register (e.g. what variable it holds):
  `SOMENAME .req Xnn`

Writing Readable Code



```
...

// absA = labs(a)
mov x0, a
bl labs
mov absA, x0
// absB = labs(b)
mov x0, b
bl labs
mov absB, x0
// sum = absA + absB
add sum, absA, absB
// return sum
mov x0, sum
ldr x30, [sp]     // Restore x30
ldr x19, [sp, 8]  // Restore x19
ldr x20, [sp, 16] // Restore x20
ldr x21, [sp, 24] // Restore x21
ldr x22, [sp, 32] // Restore x22
ldr x23, [sp, 40] // Restore x23
add sp, sp, STACKSIZE
ret
```

Problem

- Hardcoded sizes, offsets, registers are difficult to read, understand, debug

Using .equ and .req

- To define a symbolic name for a constant:
  `.equ SOMENAME, nnn`
- To define a symbolic name for a register (e.g. what variable it holds):
  `SOMENAME .req Xnn`

Writing Readable Code



```
    // Stack frame size in bytes
    .equ STACKSIZE, 48
    // Registers for parameters
    a    .req x19
    b    .req x20
    // Registers for local variables
    absA .req x21
    absB .req x22
    sum  .req x23
    // Offset sizes to save registers, in bytes
    .equ oldX19, 8
    .equ oldX20, 16
    ...

// long absadd(long a, long b)
absadd:
    // long absA, absB, sum
    sub sp, sp, STACKSIZE
    str x30, [sp]
    str x19, [sp, oldX19]
    str x20, [sp, oldX20]
    str x21, [sp, oldX21]
    str x22, [sp, oldX22]
    str x23, [sp, oldX23]
    mov a, x0
    mov b, x1
    ...
```

Problem

- Hardcoded sizes, offsets, registers are difficult to read, understand, debug

Using .equ and .req

- To define a symbolic name for a constant:
  `.equ SOMENAME, nnn`

- To define a symbolic name for a register (e.g. what variable it holds):
  `SOMENAME .req Xnn`

Writing Readable Code



```
...

// absA = labs(a)
mov x0, a
bl labs
mov absA, x0
// absB = labs(b)
mov x0, b
bl labs
mov absB, x0
// sum = absA + absB
add sum, absA, absB
// return sum
mov x0, sum
ldr x30, [sp]
ldr x19, [sp, oldX19]
ldr x20, [sp, oldX20]
ldr x21, [sp, oldX21]
ldr x22, [sp, oldX22]
ldr x23, [sp, oldX23]
add sp, sp, STACKSIZE
ret
```

Problem

- Hardcoded sizes, offsets, registers are difficult to read, understand, debug

Using .equ and .req

- To define a symbolic name for a constant:
  `.equ SOMENAME, nnn`
- To define a symbolic name for a register (e.g. what variable it holds):
  `SOMENAME .req Xnn`

Summary



Function calls in AARCH64 assembly language

Calling and returning

- `bl` instruction saves return address in X30 and jumps
- `ret` instruction jumps back to address in X30

Passing arguments

- Caller copies args to caller-saved registers (in prescribed order)
- Unoptimized pattern:
  - Callee pushes args to stack
  - Callee uses args as positive offsets from SP
  - Callee pops args from stack
- Optimized pattern:
  - Callee keeps args in callee-saved registers
  - Be careful ...

Summary (cont.)



Storing local variables

- Unoptimized pattern:
  - Callee pushes local vars onto stack
  - Callee uses local vars as positive offsets from SP
  - Callee pops local vars from stack
- Optimized pattern:
  - Callee keeps local vars in callee-saved registers

Returning values

- Callee places return value in X0
- Caller accesses return value in X0