Code Generation for Function Calls and Typing Functions

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Lyon 1

ENS DE LYON

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[1]Slides borrowed from Matthieu Moy and Laure Gonnord

Function calls: goal

```c
void sub_prog() {
      /* ... */
      return; /* back to after call to sub_prog */
}

void sub_prog2() {
      /* ... */
} /* back to after call to sub_prog2 */

int main(void) {
      sub_prog(); /* jumps to start of sub_prog */
      sub_prog2(); /* same for sub_prog2 */
      return 0;
}
```

First attempt: jump

```
sub_prog:
      li t1, 42
      j after_sub_prog

sub_prog2:
      li t1, 43
      j after_sub_prog2

      .globl main
main:
      j sub_prog # Jump
after_sub_prog:

      j sub_prog2
after_sub_prog2:

      ret # end of main
```

First attempt: jump

```
sub_prog:
      li t1, 42
      j after_sub_prog

sub_prog2:
      li t1, 43
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      .globl main
main:
      j sub_prog # Jump
after_sub_prog:

      j sub_prog2
after_sub_prog2:

      ret # end of main
```

Question

What's the problem?

Second attempt: a register for the return address

```
sub_prog:
      li t0, 42
      jr ra


      .globl main
main:
      ## la = Load address
      la ra, after_sub_prog
      j sub_prog
after_sub_prog:
      ## Second call to the
      ## same sub-program
      la ra, after_sub_prog2
      j sub_prog
after_sub_prog2:

      ret # end of main
```

Second attempt: a register for the return address

```
sub_prog:
      li t0, 42
      jr ra


      .globl main
main:
      ## la = Load address
      la ra, after_sub_prog
      j sub_prog
after_sub_prog:
      ## Second call to the
      ## same sub-program
      la ra, after_sub_prog2
      j sub_prog
after_sub_prog2:

      ret # end of main
```

Question

What's the limitation?

Second attempt: a register for the return address

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sub_prog:
      li t0, 42
      jr ra


      .globl main
main:
      ## la = Load address
      la ra, after_sub_prog
      j sub_prog
after_sub_prog:
      ## Second call to the
      ## same sub-program
      la ra, after_sub_prog2
      j sub_prog
after_sub_prog2:

      ret # end of main
```

Question

> What about recursive calls?

Recursive or Nested Calls?

```
nested_sub_prog:
      li t0, 43
      jr ra


sub_prog:
      li t0, 42
      ## Override ra set in main
      la ra, after_sub_prog2
      j nested_sub_prog
after_sub_prog2:
      ## return to main... or not.
      jr ra


      .globl main
main:
      la ra, after_sub_prog
      j sub_prog
after_sub_prog:
      ret
```

Recursive or Nested Calls?

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nested_sub_prog:
    li t0, 43
    jr ra

sub_prog:
    li t0, 42
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    la ra, after_sub_prog2
    j nested_sub_prog
after_sub_prog2:
    ## return to main... or not.
    jr ra

    .globl main
main:
    la ra, after_sub_prog
    j sub_prog
after_sub_prog:
    ret
```

Warning

It's not sufficient, but before solving the problem let's simplify notations...

Meta-instruction `call` & `ret` in RiscV

- Meta-instruction `call` *label*:
  - Equivalent to `la ra, `*next-addr*` + j `*label*
  - Loads return address into register `ra`, jumps to *label*
  - Return address = address right after the `call`
- Meta-instruction `ret`:
  - Equivalent to `jalr zero, ra, 0`
  - Jumps to the address contained in `ra`

```
sub_prog:
      li t0, 42
      call nested_sub_prog
      ## return to main?
      ret

      .globl main
main:
      call sub_prog
      ret
```

Meta-instruction `call` & `ret` in RiscV

- Meta-instruction `call` *label*:
  - Equivalent to `la ra, next-addr` + `j` *label*
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  - Return address = address right after the `call`
- Meta-instruction `ret`:
  - Equivalent to `jalr zero, ra, 0`
  - Jumps to the address contained in `ra`

```
sub_prog:
      li t0, 42
      call nested_sub_prog
      ## return to main?
      ret

      .globl main
main:
      call sub_prog
      ret
```

Question

? Nice, but does not change our problem!

Digression

- In some instruction sets (e.g. Intel), call/ret save and restore address on stack. Then, it "works magically".
- RISCV = <u>Reduced</u> Instruction Set Chip, version V $\Rightarrow$ we need more work by hand.

Saving return address on stack

```
      ## Should save/restore too
nested_sub_prog:
      li t0, 43
      ret

sub_prog:
      ## push ra on stack
      addi sp, sp, -8
      sd ra, 0(sp)

      ## Function's body
      li t0, 42
      call nested_sub_prog

      ## pop ra from stack
      ld ra, 0(sp)
      addi sp, sp, 8
      ret
```

```
                          .globl main
main:
      addi sp, sp, -8
      sd ra, 0(sp)

      call sub_prog

      ld ra, 0(sp)
      addi sp, sp, 8
      ret
```
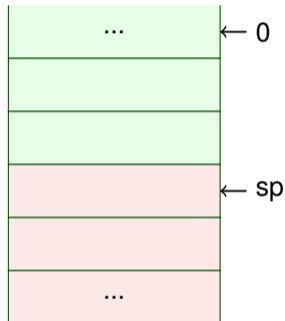
Stack during function calls

Before `call` + save `ra`
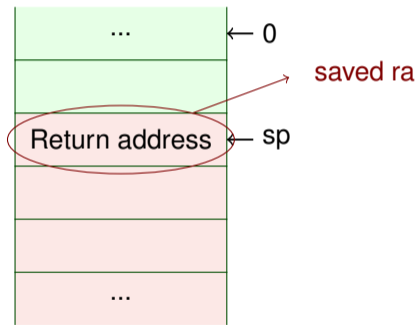
Stack during function calls

Before call + save ra

...	← 0
	← sp
...	

After call + save ra

...	← 0
Return add (ra)	← sp
...	
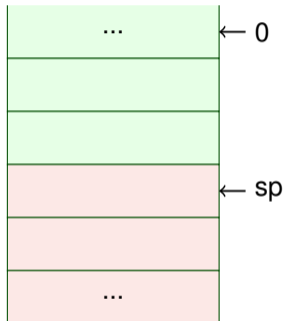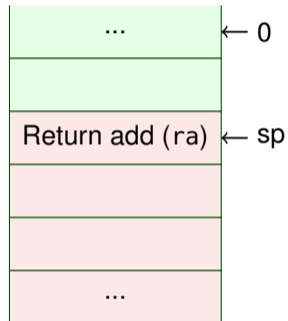
return address = address following call
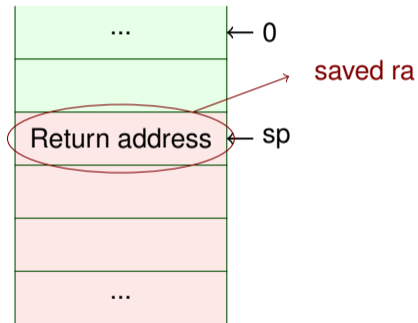
Stack and `ret` instruction

Before `ret` + restore `ra`

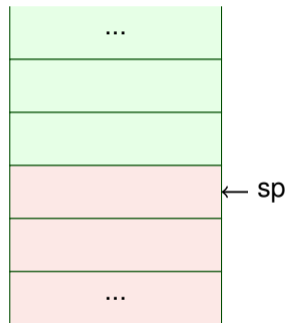# Stack and `ret` instruction

Before `ret` + restore `ra`   After `ret` + restore `ra` ($\approx$ "pop `ra`")

call and ret : Example

```
     ## Should save/restore too
nested_sub_prog:
     li t0, 43
     ret

sub_prog:
     ## push ra on stack
     addi sp, sp, -8
     sd ra, 0(sp)

     ## Function's body
     li t0, 42
     call nested_sub_prog

     ## pop ra from stack
     ld ra, 0(sp)
     addi sp, sp, 8
     ret
```

```
$ spike -d pk ./a.out
: until pc 0 10162 <- sub_prog
: reg 0 sp
0x000000007f7e9b48
: reg 0 ra
0x0000000000010188
: mem 0 000000007f7e9b48
0x0000000000010106
: mem 0 000000007f7e9b40
0x0000000000000000
core 0: 0x00010162 c.addi  sp, -8
core 0: 0x00010164 c.sdsp  ra, 0(sp)
: reg 0 sp
0x000000007f7e9b40
: reg 0 ra
0x0000000000010188
: mem 0 000000007f7e9b48
0x0000000000010106
: mem 0 000000007f7e9b40
0x0000000000010188
[...]
```

call and ret : Example

```
      ## Should save/restore too
 nested_sub_prog:
      li t0, 43
      ret

 sub_prog:
      ## push ra on stack
      addi sp, sp, -8
      sd ra, 0(sp)

      ## Function's body
      li t0, 42
      call nested_sub_prog

      ## pop ra from stack
      ld ra, 0(sp)
      addi sp, sp, 8
      ret
```

```
$ spike -d pk ./a.out
[...]
: reg 0 ra
0x0000000000010188
[...]
core 0: 0x00010166 li    t0, 42
core 0: 0x0001016a jal   pc -0xe
core 0: 0x0001015c li    t0, 43
core 0: 0x00010160 ret
: reg 0 ra
0x000000000001016e
core 0: 0x0001016e c.ldsp ra, 0(sp)
core 0: 0x00010170 c.addi sp, 8
: reg 0 ra
0x0000000000010188
core 0: 0x00010172 ret
core 0: 0x00010188 li    a0, 101
```

1 Code "generation" for function calls

- Function Calls and Return
- Stack, local variables, parameters
- Local Variables
- Register Saving&Restoring
- Parameter Passing
- RiscV Calling Conventions
- Summary

Local variables: first (failed) attempt without stack

```
int f() {                              f:
  a = ...;                                 mv ..., t0

  ... a ...;                               ... t0 ...
}                                          ret

int g() {                              g:
  b = ...;                                 mv ..., t0

  ... b ...;                               ... t0 ...
}                                          ret
```

- What if f calls g?
- What if we have more variables than registers?
- What if we were in real C and have &x operator?
- ⇒ Not viable as-is.

Variables accessible by a function

```
int global;
int main() {
   int local;
   ...
};
```

- Global variables

- Local variables

- Parameters ($\approx$ local variables set by caller)

Variables accessible by a function

```
int global;
int main() {
   int local;
   ...
};
```

- Global variables
  ⇒ Exist in 1 and only 1 sample. Easy management with labels pointing to static data.

- Local variables

- Parameters (≈ local variables set by caller)

Variables accessible by a function

```
int global;
int main() {
    int local;
    ...
};
```

- Global variables

    $\Rightarrow$ Exist in 1 and only 1 sample. Easy management with labels pointing to static data.

- Local variables

- Parameters ($\approx$ local variables set by caller)

    $\Rightarrow$ Only exist when function is being called

Address of Local Variables

Forget about register allocation for now, and assume all variables are stored in memory. Registers are used for temporaries. More on that later.

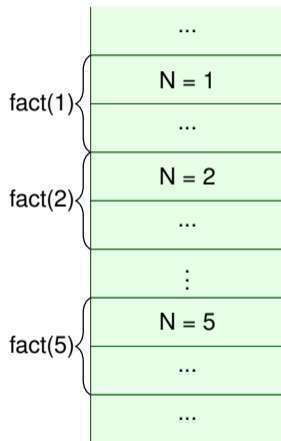## Local Variables $\neq$ Global Variables

```
int fact(int N) {
   int res;
   if (N <= 1) {
      res = 1;
   } else {
      res = N;
      res = res * fact(N -1);
   }
   return res;
}
```

- fact(5) calls fact(4) which calls
  fact(3) ... $\Rightarrow$ several values for N at
  the same time in memory.

Local Variables $\neq$ Global Variables

```c
int fact(int N) {
   int res;
   if (N <= 1) {
      res = 1;
   } else {
      res = N;
      res = res * fact(N -1);
   }
   return res;
}
```

- `fact(5)` calls `fact(4)` which calls
  `fact(3)` ... $\Rightarrow$ several values for N at
  the same time in memory.

Address of Local Variables

- Absolute address:
  - $\Rightarrow$ impossible, address isn't constant
- Relative to sp:
  - $\Rightarrow$ Possible[2], but painful: sp may change too often.
- Solution: address relative to the frame pointer fp
  - fp is set when entering a function
  - ... and restored before return

---

[2]done by gcc -fomit-frame-pointer for example
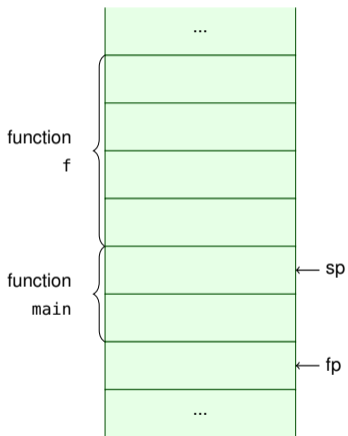
Management of sp / fp: Function Calls

```
main: # ...
    call f
    # ...

f:  addi sp, sp, -32
    sd ra, 0(sp)
    sd fp, 8(sp)
    addi fp, sp, 32
    # Body of f: loc2 = loc1
    ld t0, -8(fp)
    sd t0, -16(fp)

    ld fp, 8(sp)
    ld ra, 0(sp)
    addi sp, sp, 32
    ret
```
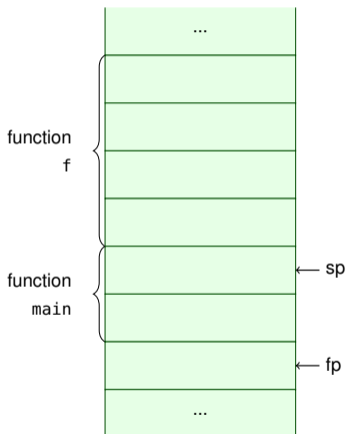
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```
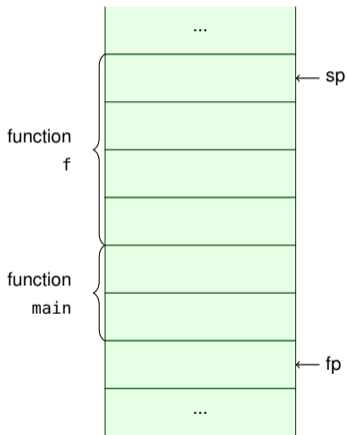
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      ret
```

Management of `sp` / `fp`: Function Calls

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    ld ra, 0(sp)
    addi sp, sp, 32
    ret
```
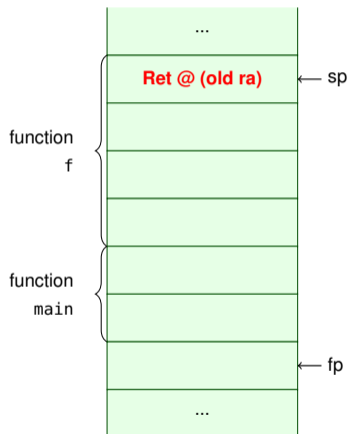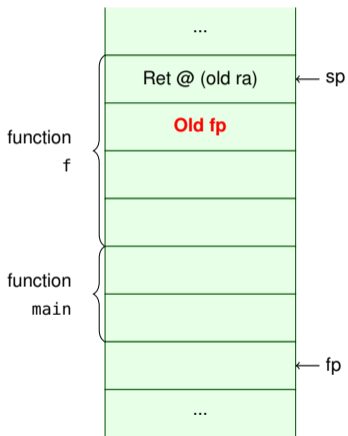
Management of sp / fp: Function Calls

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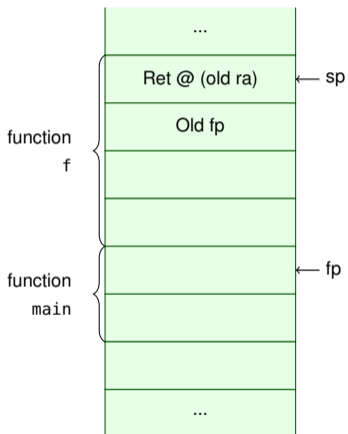
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```

Management of sp / fp: Return from Functions

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main: # ...
     call f
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    addi sp, sp, 32
    ret
```

Management of sp / fp: Return from Functions

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    ld ra, 0(sp)
    addi sp, sp, 32
    ret
```
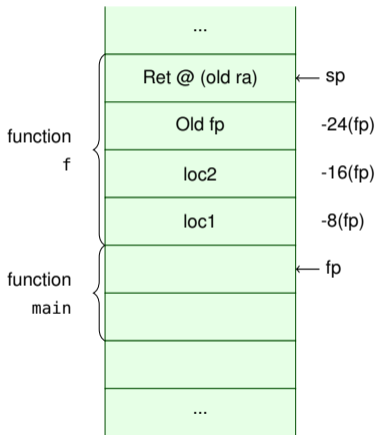
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    ld fp, 8(sp)
    ld ra, 0(sp)
    addi sp, sp, 32
    ret
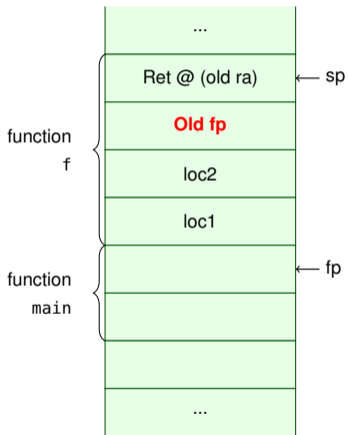```
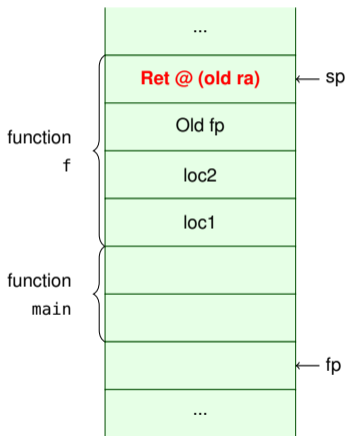
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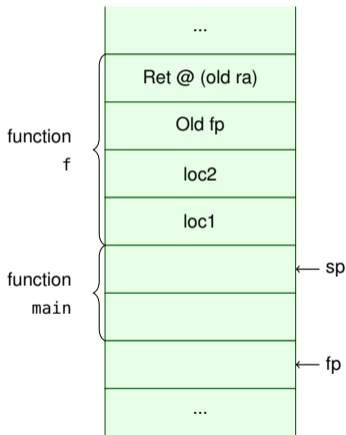
# Stack Frame

Stack frame = set of data
accessible by a function

- Created on function call
- "Destroyed" on function
  return
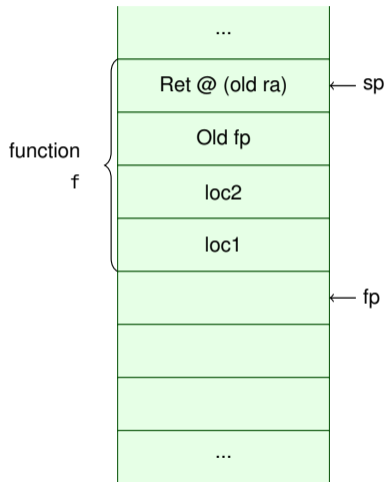
| ... |
|:---:|
| Ret @ (old ra) | ← sp
| Old fp |
| loc2 |
| loc1 |

function
f

← fp

| |
|:---:|
| |
| |
| ... |

# Register Saving&Restoring

- Problem: Register = global variable in the CPU

```
li t0, 42
call f # may use t0
sd t0, ... # may not be 42 anymore
```

- When to save?
    - By the caller, before the call:
      ⇒ Restored by caller, after the call.
    - By the callee, at the beginning of the function:
      ⇒ Restored by the callee, before the end of function (ret).

Register Saving&restoring by the caller

```
# Register saving before the call
sd t0, 16(sp)
sd t1, 24(sp)

call f

# Restoring, after the call
ld t1, 24(sp)
ld t0, 16(sp)
```
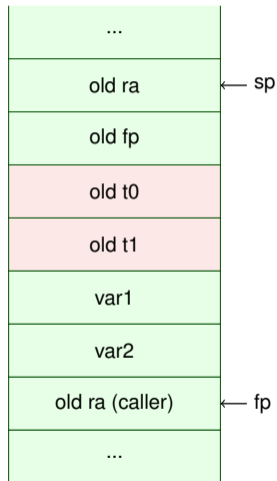
Save&Restore by the Callee

```
f: addi sp, sp, -48
   sd ra, 0(sp)
   sd fp, 8(sp)
   addi fp, sp, 48

   # Save
   sd s1, 16(sp)
   sd s2, 24(sp)

   # Body of f
```

```
   # Restore
   ld s2, 24(sp)
   ld s2, 16(fp)

   # return from f
   ld fp, 8(sp)
   ld ra, 0(sp)
   addi sp, sp, 48
   ret
```
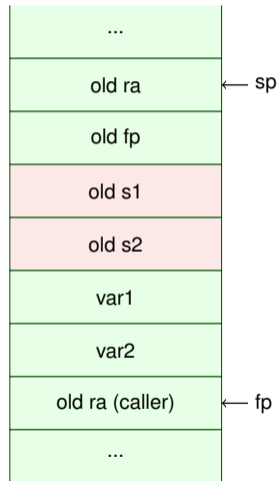
...
old ra	← sp
old fp
old s1
old s2
var1
var2
old ra (caller)	← fp
...

Register Saving Conventions

Caller/Callee saving: what shall we chose?

- Caller and callee need to follow the same convention!
- Convention can be different for different registers:
  - "scratch" (aka volatile, aka caller-saved) $\Rightarrow$ the callee doesn't have to save/restore. The callee needs to save/restore if needed.

  - "non scratch" (aka callee-saved) $\Rightarrow$ The callee must save any register it uses.

Register Saving Conventions

Caller/Callee saving: what shall we chose?

- Caller and callee need to follow the same convention!
- Convention can be different for different registers:
    - "scratch" (aka volatile, aka caller-saved) $\Rightarrow$ the callee doesn't have to save/restore. The callee needs to save/restore if needed.
      In RiscV: ra, ti, $i \in 0..6$. t = **t**emporary
    - "non scratch" (aka callee-saved) $\Rightarrow$ The callee must save any register it uses.
      In RiscV: sp, fp, si, $i \in 1..11$ (remember that s0 is another name for fp). s = **s**aved.

Save&Restore: Big Picture

```
f: # ... (room for at least 160 bytes)
   sd s1, 16(sp)
   sd s2, 24(sp)
   # ...
   sd s11, 96(sp)

   # Call function g
   sd t0, 104(sp)
   sd t1, 112(sp)
   # ...
   sd t6, 152(sp)
   call g
   ld t1, 112(sp)
   ld t0, 104(sp)

   ld s2, 24(sp)
   ld s1, 16(sp)
   # ...
```
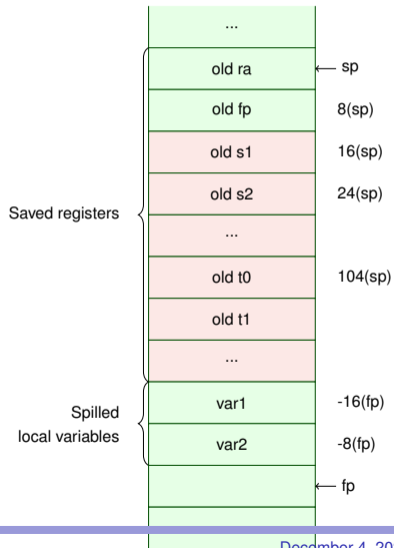
Hmm, Save&Restore Everything, Really?

- Save&Restore everything: each stack-frame = 160 bytes + actual variables (not counting floating-point registers).
- Easy optimization:
  - Save si registers only if used somewhere in the function.
  - Save ti registers only if live at the call site.
  - Don't save ti when no function is called.
- In the lab: go for brute-force, save everything!

Local Variables Vs Registers

- Remember register allocation: variables can be (cleverly) allocated to registers, not just in memory...
- ... but we need one instance of variable per stack-frame.

Local Variables Vs Registers

- Remember register allocation: variables can be (cleverly) allocated to registers, not just in memory...

- ... but we need one instance of variable per stack-frame.

- Registers are saved (by caller or callee) $\Rightarrow$ virtually one register instance per stack frame $\Rightarrow$ allocate variables just like before for each function, it works.

Local Variables Vs Registers

- Remember register allocation: variables can be (cleverly) allocated to registers, not just in memory...

- ... but we need one instance of variable per stack-frame.

- Registers are saved (by caller or callee) $\Rightarrow$ virtually one register instance per stack frame $\Rightarrow$ allocate variables just like before for each function, it works.

- In real-life, constructs like C's & (address of) operator may also force allocation in the stack.

1. Code "generation" for function calls
   - Function Calls and Return
   - Stack, local variables, parameters
   - Local Variables
   - Register Saving&Restoring
   - Parameter Passing
   - RiscV Calling Conventions
   - Summary

Parameter Passing

- Function parameter = local variable assigned from callee
- Same as local variables: in stack or in register
- RiscV: pass parameters using registers ai ($i \in 0..7$), use stack only if more than 8 parameters.
- Return value = value in the callee, assigned from caller
- RiscV: return value in $a0$

Parameter Passing: Example

```
f: # ...

  # x = g(42, 666)
  li a0, 42
  li a1, 666
  call g
  ld ``x'', a0
  # ...

g: # ...
  # use a0 and a1 to
  # access parameters.
```

Note: here and in the next slides we use "variables". So it is not strictly assembler
(needs some register allocation for example).

Parameter Passing + Saving&Restoring

What doesn't not work

```
f: # ...

   # g(h(), i(), j())
   call h
   mv a0, a0 # or not
   call i
   mv a1, a0 # Oops, call i just destroyed a0
   call j # may destroy a1 too
   mv a2, a0
   call g
   # ...

g: # ...
   # use a0 and a1 to
   # access parameters.
```

Parameter Passing + Saving&Restoring

```
# g(h(), i(), j())

# First, Evaluate args:
call h
mv temp_0, a0
call i
mv temp_1, a0
call j
mv temp_2, a0
```

```
# Then, do pass arguments:
mv a0, temp_0
mv a1, temp_1
mv a2, temp_2
# Save registers
sd t0, 104(sp)
sd t1, 112(sp)
call g
mv temp_3, a0
```

Pass-by-Value, Pass-by-Address

- Pass-by-value: copy the value of the argument to pass it to the callee
  - Original value is unmodified
  - Done for scalar types in C (`void f(int x)`)
- Pass-by-address: give the <u>address</u> of the argument to the callee
  - Modifications done in the callee are visible to the caller
  - Avoids cost of copy for large data
  - Done manually in C (`void f(int *x)`) or by the compiler when using references (`void f(int &x)`)
  - Arrays are always passed by address in C

Example: `increment(int &x) {x++;}`

```
increment:                            main:
  addi sp, sp, -16                      addi sp, sp, -32
  sd ra, 0(sp)                          sd ra, 0(sp)
  sd fp, 8(sp)                          sd fp, 8(sp)
  addi fp, sp, 16                       addi fp, sp, 32
                                        sd s1, 16(sp)
  # Read args to temporaries
  mv t0, a0                             # int x = 42; x stored at -8(fp)
                                        li t0, 42
  # Body                                sd t0, -8(fp)
  lw t1, (t0)
  addi t1, t1, 1                        # increment(x)
  sw t1, (t0)                           addi a0, fp, -8 # Address of x
                                        call increment
  ld fp, 8(sp)
  ld ra, 0(sp)                          # return x;
  addi sp, sp, 16                       ld a0, -8(fp)
  ret
```

Calling Conventions, aka Application Binary Interface

- Calling convention (ABI, Application Binary Interface) = conventions imposed for data representation and allocation in memory.
- Needed to get the caller and callee to work together (e.g. caller compiled with GCC, callee compiled with LLVM, will it work?[3])
- May impose:
  - A number of system calls and how to perform them
  - Memory addresses usable by a program
  - Registers usage convention
  - Stack conventions

---

[3]Same question when mixing GCC and your compiler ...

RiscV ABI

- Format of a stack frame as described here.
- Stack pointer always multiple of 16 (add 8 bytes of padding if needed)
- Parameters passed in ai
- Return value passed through a0
- ti, $i \in 0..6$ are caller-saved
- si, $i \in 1..11$ are callee-saved ($sp = s0$)

See "RISC-V User-Level ISA, Chapter 18, Calling Convention"
https://riscv.org/wp-content/uploads/2015/01/riscv-calling.pdf

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Code for a Function Body

```
f: addi sp, sp, -XXX # Adjust XXX to size of stack frame
   sd ra, 0(sp)
   sd fp, 8(sp)
   addi fp, sp, XXX # Adjust                    # Restore s registers
                                                ld s1, 16(sp)
   # Save s registers                           ld s2, 24(sp)
   sd s1, 16(sp)                                # ...
   sd s2, 24(sp)                                ld s11, 96(sp)
   # ...
   sd s11, 96(sp)                               # Evaluate return val
                                                # in temp_41
   # Read args to temporaries                   # ...
   mv temp_0, a0                                mv a0, temp_41
   mv temp_1, a1
   # ...                                        ld fp, 8(sp)
                                                ld ra, 0(sp)
   # Body of f                                  addi sp, sp, XXX # Adjust
                                                ret
```

Code for a Function Call

```
# Evaluate args:
# ... save t registers
call h
# ... restore t registers
mv temp_0, a0
call i # + save and restore registers
mv temp_1, a0
call j # + save and restore registers
mv temp_2, a0

# Do pass arguments
mv a0, temp_0
mv a1, temp_1
mv a2, temp_2
```

```
# Save t registers
sd t0, 104(sp)
sd t1, 112(sp)
# ...
sd t6, 152(sp)
# Actual call
call g

# Restore t registers
ld t0, 104(sp)
ld t1, 112(sp)
# ...
ld t6, 152(sp)
# Get return value
mv temp_3, a0
```