Compiler Design

Lecture 14:
Code generation : Function call and Memory management (EaC Chapter 6&7)

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Function calls

Function calls

```
// callee
int bar(int a) {
    return 3+a;
}

// caller
void foo() {
   ...
   bar(4)
   ...
}
```

- foo is the caller
- bar is the callee

What happens during a function call?

- The caller needs to pass the arguments to the callee
- The callee needs to pass the return value to the caller

But also:

- The values stored in registers needs to be saved somehow.
- Need to remember where we came from to return to the call site.

Call stack recap

Stack grows towards the lower addresses

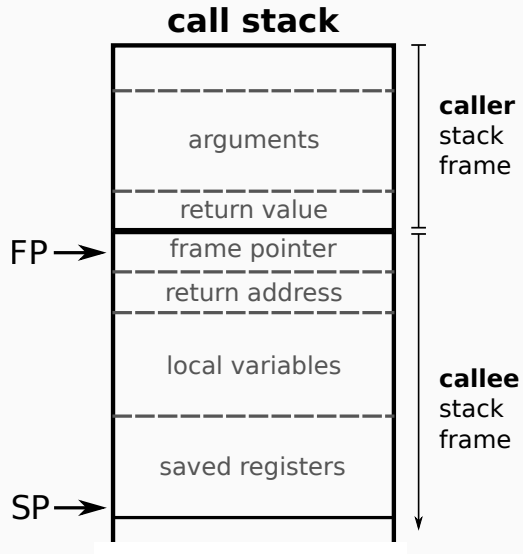
- Oppposite to the heap

Stack Pointer (SP)

- Always points to the top of the stack.
- Can move while function executes:
  - push/pop operations
  - alloca()

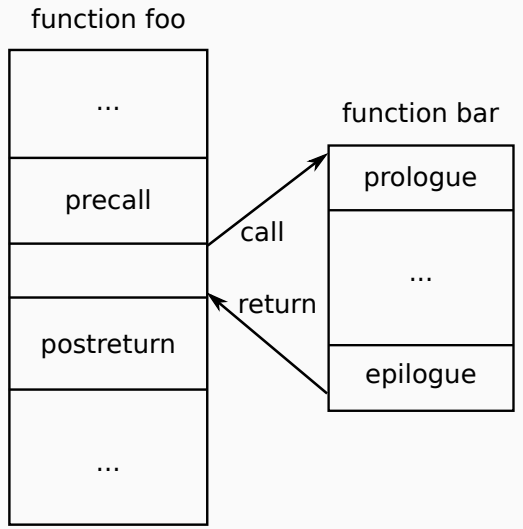
Frame Pointer (FP)

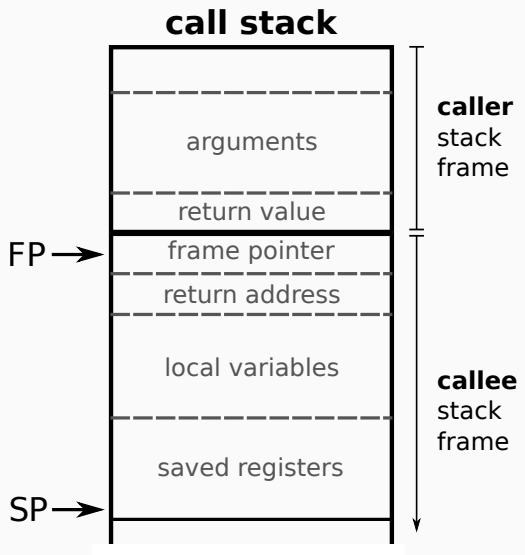
- The frame pointer in initiazed to the SP upon entering the function.
- Guaranteed not to change during execution of the function.
- Can be used to refer to objects on the stack: arguments, return value or local variables.



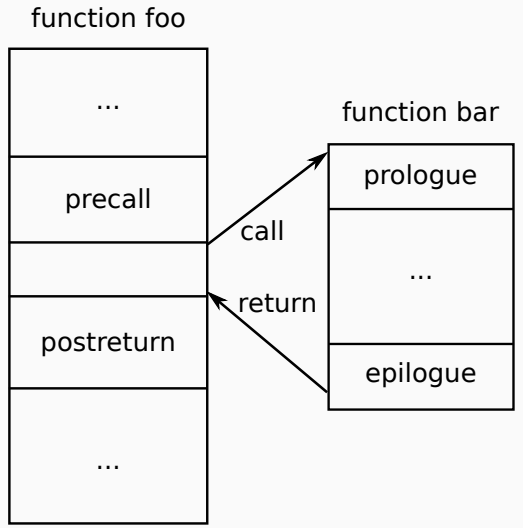
Possible convention: **Callee-save**

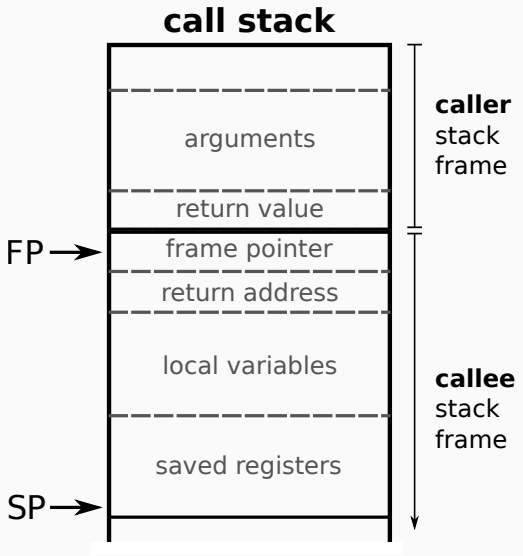
- precall:
  - pass the arguments via registers or push on the stack
  - reserve space on stack for return value (if needed)
- postreturn:
  - read the return value from dedicated register or stack
  - reset stack pointer





- prologue:
  - push frame pointer onto the stack
  - initialise the frame pointer
  - push return address on the stack (if function makes call)
  - reserve local variables space on stack
  - push saved registers on stack
- epilogue:
  - restore saved registers from the stack
  - restore return address from the stack (if function makes call)
  - restore the stack pointer
  - restore the frame pointer from the stack





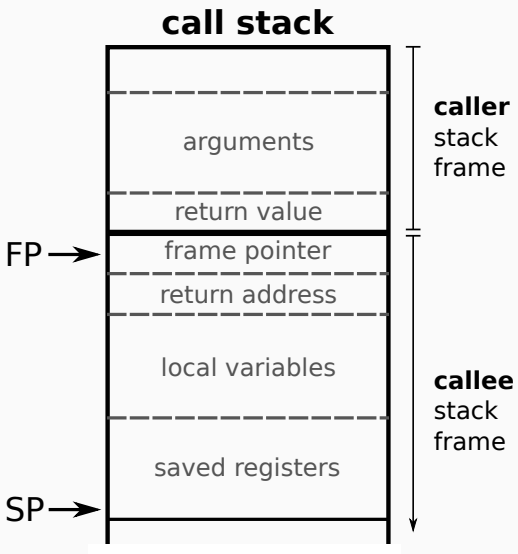
Other conventions are possible.

For your project, we suggest you:

- pass all arguments and return value via the stack
  (needed anyway when more than four arguments);
- always push/restore the return address
  (needed anyway when the function calls another one).

Example (callee)

```
int bar(int a) {
   int b;
   return 3+a;
}
```

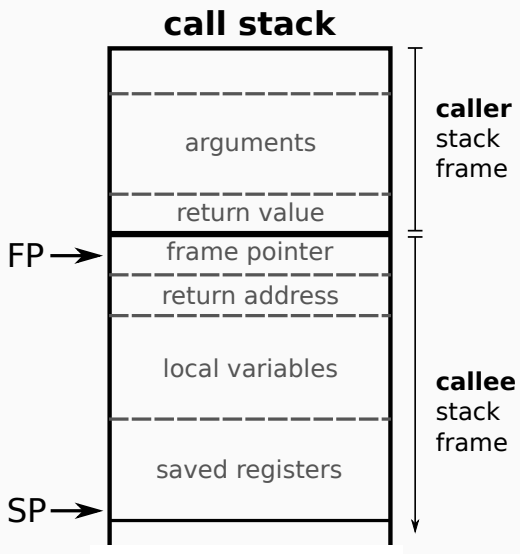


Assembly code:

```
bar:

addi $sp, $sp, -4   #
sw   $fp, ($sp)     # push frame pointer on the stack

move $fp, $sp       # initialise the frame pointer

addi $sp, $sp, -4   #
sw   $ra, ($sp)     # push return address on stack

addi $sp, $sp, -4   # reserve space on stack for b

addi $sp, $sp, -4   #
sw   $t0, ($sp)     # push $t0 onto the stack
addi $sp, $sp, -4   #
sw   $t1, ($sp)     # push $t1 onto the stack

li   $t0, 3         # load 3 into $t0

lw   $t1, 8($fp)    # load first argument from stack
add  $t0, $t0, $t1  # add $t0 and first argument

sw   $t0, 4($fp)    # copy the return value on stack

lw   $t0, -12($fp)  # restore $t0
lw   $t1, -16($fp)  # restore $t1

addi $sp, $fp, 4    # restore stack pointer

lw   $ra, -4($fp)   # restore return address from the stack

lw   $fp, ($fp)     # restore the frame pointer

jr   $ra            # jumps to return address
```

Example (caller)

```
void foo() {
  ...
  bar(4)
  ...
}
```



Assembly code:

```
foo:
...

li   $t0, 4          # prepare argument

addi $sp, $sp, -4    #
sw   $t0, ($sp)      # push argument on stack

addi $sp, $sp, -4    # reserve space on stack for return value

jal  bar             # call function

lw   $t0, $sp        # read return value from stack

addi $sp, $sp, 8     # reset stack pointer
...
```

Beware of value semantic with functions!

Structs need to be passed by value in a function call.

C code example:

```c
struct vec_t {
  int x;
  int y;
}

int foo(struct vec_t v) {
  return v.x;
}

void bar() {
  struct vect_t myvec;
  int i;
  i = foo(myvec);
}
```

Beware of value semantic with functions!

Structs needs to be returned by value.

C code example:

```
struct vec_t {
  int x;
  int y;
}

struct vec_t foo() {
  struct vec_t v;
  v.x = 0; v.y = 1;
  return v;
}

void bar() {
  struct vect_t myvec;
  myvec = foo();
}
```

Coursework tip

Structs have to be handled differently with function calls.

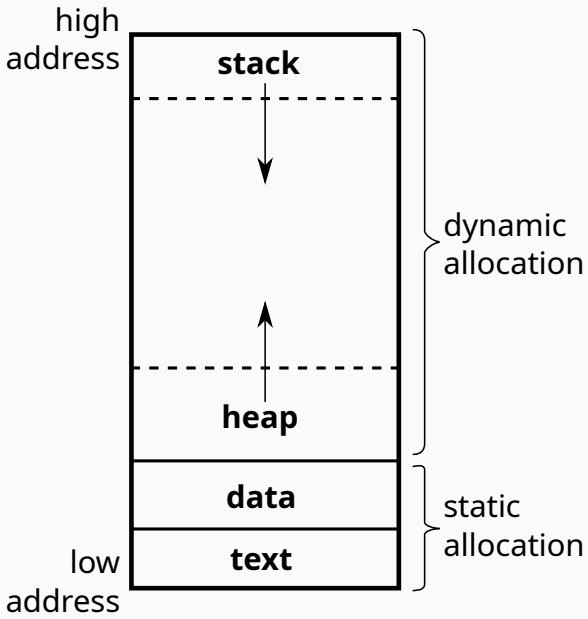
- If passed as an argument, they must be copied word by word onto the stack;
- When a `return` statement is encountered, they must be copied word by word onto the stack;
- If returned from a function, they might have to be copied word by word from the stack (*e.g.* assignment).

Memory management

Static versus Dynamic

- **Static allocation**: storage can be allocated directly by the compiler by simply looking at the program at compile-time. This implies that the compiler can infer storage size information.
- **Dynamic allocation**: storage needs to be allocated at run-time due to unknown size or function calls.

Heap, Stack, Static storage



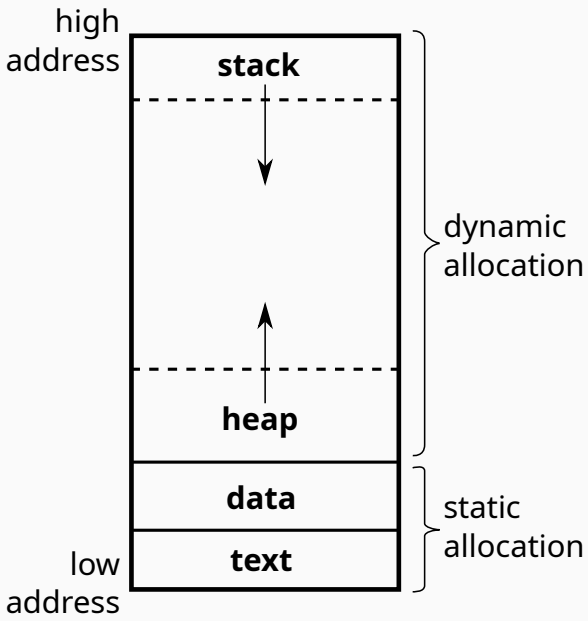
Static storage:

- Text: instructions
- Data
  - global variables
  - string literals
  - global arrays of fixed size
  - ...

Dynamic Storage:

- Heap: `malloc`
- Stack:
  - local variables
  - function arguments/return values
  - saved registers
  - register spilling (register allocation)

Example




```
char c;                          data
int arr[4];                      data
void foo() {
  int arr2[3];                   stack
  int* ptr =                     stack
    (int*) malloc(sizeof(int)*2);    heap
  ...
  {
     int b;                      stack
     ...
     bar("hello");               data
  }
  ...
}
```

Memory management

Static Allocation & Alignment

Scalars

Typically in C:

- `int` and pointer types (*e.g.* `char*`, `int*`, `void*`) are 32 bits (4 byte).
- `char` is 1 byte

Example C code (static allocation):

```
char c;
int i;
```

Assembly code:

```
.data
c: .space 1 # char
i: .space 4 # int
.text
lb $t0, c
lw $t1, i    # error!
```

Miss-aligned load, 😠 error!

```
.data
c:      .space 1 # char
.align 2         # 2^2
i:      .space 4 # int
.text
lb $t0, c
lw $t1, i    # no error
```

Padding added, all good ☺

Structures

In C, typically:

- all fields of a struct should be aligned to their size if smaller than the data alignment of the architecture (unless `packed` directive is used); and
- the size of a struct is a multiple of the maximum alignment of any of its field.

Example C code:

```
struct myStruct_t {
  char c1;
  int i;
  char c2;
};
struct myStruct_t ms;
...
ms.i
...
```

Assembly code:

```
.data
ms:  .space  12

.text
  ...
  lw $t0, (4)ms
  ...
```

Arrays

In contrast to structs, arrays are always compact in C.

Example C code (static allocation):

```
char arr[7];
...
```

Corresponding assembly code:

```
.data
arr: .space 7

.text
...
```

Summary

When dealing with allocation of data:

- make sure all declarations/fields are aligned to their size

For variables: padding/alignment may be required before a global or local allocation;

For structs: the total size of the struct and the offset of each field must take into account padding/alignment.

Memory management

Stack allocation

Stack variable allocation

The compiler needs to keep track of local variables in functions.

These cannot be allocated statically (static = text section).

```
int foo(int i) {
  int a;
  a = 1;
  if (i==0)
    foo(1);
  print(a);
  a = 2;
}
void bar() {
  foo(0);
}
```

If a allocated statically, what is printed?

1

2

There must be one copy of a local variable per function call

$\Rightarrow$ local variables must be stored on the stack!

How to keep track of local variables on the stack?
⇒ Could use the `stack pointer`.

⚠ Problem: stack pointer can move, *e.g.*:

- dynamic memory allocation on the stack
- push/pop instructions

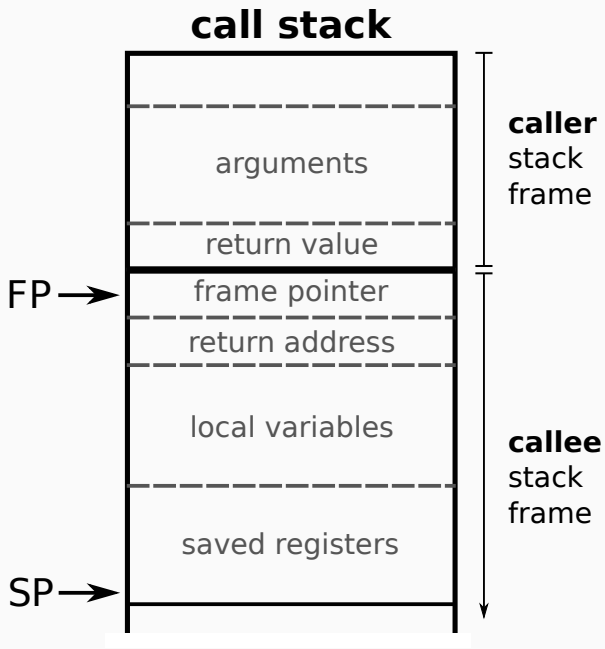
Solution: use another pointer, the frame pointer

Frame pointer

- The frame pointer must be initialised to the value of the stack pointer, just when entering the function.
- Access to variables allocated on the stack can then be determined as a fixed offset from the frame pointer.

The frame pointer (FP) always points to the start of the *callee* stack frame.

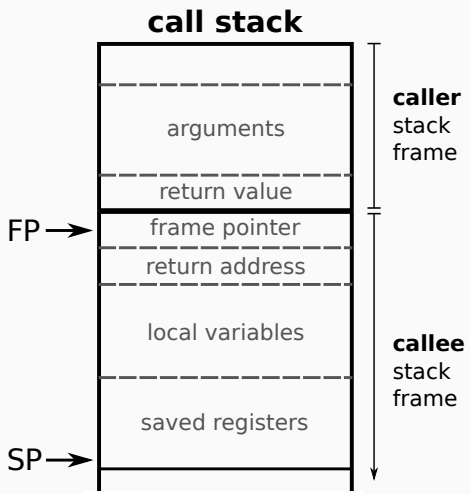
The stack pointer (SP) always points at the top of the stack (points to the last element pushed).



Static (global) vs Stack (local) allocation

```
int global_array[8];

void foo(){
  int local_array[8];
  ...
  global_array[3]
  ...
  local_array[3]
  ...
}
```

```
global_array:    .space 32

foo:
...
# global_array[3]
li   $t0, #3
la   $t1, global_array
mul  $t2, $t0, #4
add  $t3, $t1, $t2
lw   $t4, ($t3)
...
# local_array[3]
li   $t0, #3
addi $t1, $fp, -36 # start of local_array
mul  $t2, $t0, #4
add  $t3, $t1, $t2
lw   $t4, ($t3)
...
```

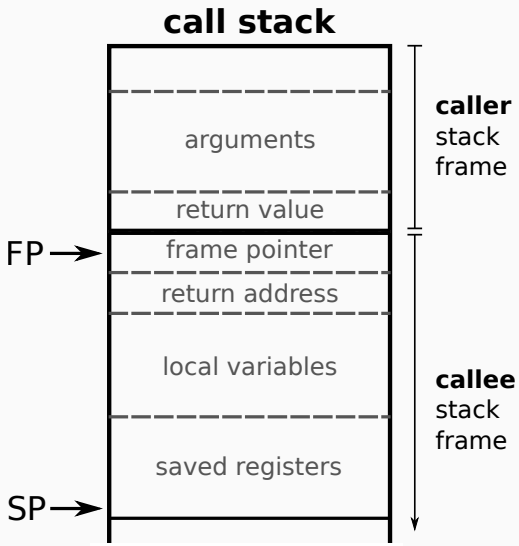


In both cases, the base address of a variable is always the lowest address.

Memory management

Memory allocation pass

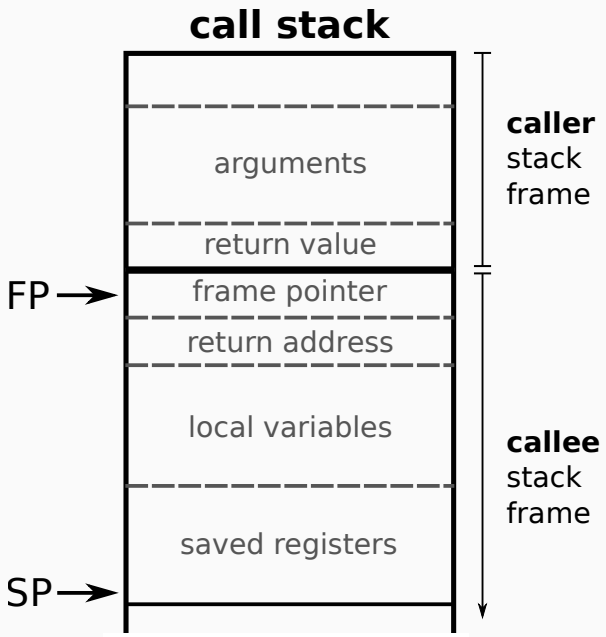
Memory Allocator



Args in reverse order from **FP**

```
class Allocator {
 int fpOffset;
 boolean insideFunDecl = false;

 void visit(ASTNode node) {
  switch(node) {
   case FunDecl fd -> {

    fd.retValFPOffset = +4;

    int offset = 4+fd.returnSize;
    for (param: fd.params.reverse) {
      param.fpOffset = offset;
      offset += param.size;
    }

    this.fpOffset = -4;
    this.insideFunDecl = true;
    visit(fd.body);
    this.insideFunDecl = false;
  }
  ...
```

Memory Allocator



Low address is “start” of variable

(think of structs!)

```
...
case VarDecl vd -> {
  if (insideFunDecl) {// local/stack
    this.fpOffset -= vd.size;
    vd.fpOffset = this.fpOffset;
  } else {// global/static
    Label label = new Label(vd.name);
    ... // emit .space label size
    vd.label = label;
  }
}
case default -> {
  for (c: node.children)
    visit(c);
  }
...
```

Memory management

Address of expressions

Generating addresses

Sometimes, the compiler needs to know the address of an expression (*e.g.* assignment, address-of operator):

```
struct vec_t {
  int x;
  int y;
};

void foo() {
  int i;
  struct vec_t v;
  int arr[10];

  i = 2;
  v.x = 3;
  arr[2] = 5;
}
```

Generating addresses

Specialized generator that produces the address of an expression:

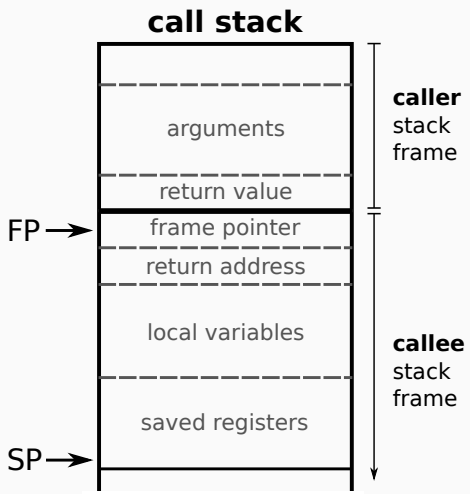
Address Code Generator

```
class AddrCodeGen {

  Register visit(Expr e) {
    return switch(e) {
      case BinOp bo -> {
        error("No address for BinOP"); yield INVALID;}
      case IntLiteral il -> {
        error("No address for IntLiteral"); yield INVALID;}
      case VarExpr v -> {
        Register resReg = newVirtualRegister();
        if (v.vd.isStaticAllocated())
          emit("la", resReg, v.vd.label);
        else if (v.vd.isStackAllocated())
          emit("addi", resReg, Register.fp, v.vd.fpOffset);
        yield resReg;
      }
      ...
    }
  }
```

Static (global) vs Stack (local) allocation

```
int global_array[8];

void foo(){
  int local_array[8];
  ...
  global_array[3]
  ...
  local_array[3]
  ...
}
```

```
global_array:    .space 32

foo:
...
# global_array[3]
li   $t0, #3
la   $t1, global_array
mul  $t2, $t0, #4
add  $t3, $t1, $t2
lw   $t4, ($t3)
...
# local_array[3]
li   $t0, #3
addi $t1, $fp, -36 # start of local_array
mul  $t2, $t0, #4
add  $t3, $t1, $t2
lw   $t4, ($t3)
...
```



In both cases, the base address of a variable is always the lowest address.

`AddrCodeGen` is called from the other code generator when needed:

ExprCodeGen

```
...
case Assign a -> {
  Register addrReg = (new AddrCodeGen()).visit(a.lhs);
  Register valReg  = visit(a.rhs);
  emit("sw", valReg, addrReg);
  return valReg;
}
...
```

Last words

Examples above have assumed variable stores an interger.

In case a variable represents an array or struct, you have to be careful:

- array are passed by reference
  (treat them exactly like pointers, no big deal)
- structs are passed by values

Assigning between two structs means copying field by field. Hence your code generator must check the type of variables when encountering an assignment and handle structures correctly.

Similar problem for struct and function call. Arguments and return values that are struct are passed by values.

Code with struct assignment:

```
struct vec_t {
  int x;  int y;
};
void foo() {
  struct vec_t v1;
  struct vec_t v2;
  v1 = v2;
}
```

Equivalent to:

```
struct vec_t {
  int x;  int y;
};
void foo() {
  struct vec_t v1;
  struct vec_t v2;
  v1.x = v2.x;
  v1.y = v2.y;
}
```

Tip for coursework

The register returned by the ExprCodeGen visit method holds the expression's value. However, a structure cannot be held in a register.

- As a special case, the ExpCodeGen's visit method should return the address of a `StructType` expr;
- And the AddrCodeGen will handle the assignment (and other things).

```
class ExprCodeGen {
  Register visit(Expr e) {
    if (e.type == StructType)
      return (new AddrCodeGen()).visit(e);
    ...
} }
```

```
class AddrCodeGen {
  Register visit(Expr e) {
    return switch(e) {
      case Assign a -> {
        Register lhsAddrReg = visit(a.lhs);
        if (a.type == StructType) {
          Register rhsAddrReg = visit(a.rhs);
          // copy the struct word by word
          ...
        } else { // not a struct
          Register rhsValueReg = (new ExprCodeGen()).visit(a.rhs);
          // copy the value of the rhs into memory at address lhs
          ...
        }
        yield lhsAddrReg;
 } } }
```

Next lecture

Naive register allocator.