



# Compiler construction

## Lecture 5: Project extensions

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### This lecture



Some project extensions:

- Arrays
- Pointers and structures
- Object-oriented languages
- Module system (extension proposal)

### Warm-up: Boolean expressions and control flow



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#### Possible code generation for one-armed if stmt

```
cgStmt (Cond expr stmt) = do
  then_ <- newLabel
  k <- newLabel
  cgBoolExpr then_ k expr
  label then_
  cgStmt stmt
  branch k
  label k
```

### Warm-up: Boolean expressions and control flow



#### Possible code generation for one-armed if stmt

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cgStmt (Cond expr stmt) = do
  then_ <- newLabel
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  label then_
  cgStmt stmt
  branch k
  label k
```

#### Possible code for conjunction in condition expression

```
cgBoolExpr then_ k (EAnd x y) = do
  mid <- newLabel
  cgBoolExpr mid k x
  label mid
  cgBoolExpr then_ k y
```

## Arrays

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## Memory structure



### JVALETTE restrictions

- Only local variables and parameters – no global variables or other non-local declarations
- Only simple data types (`int`, `double`, `boolean`) with fixed-size values
- Only call-by-value parameter passing

As a consequence, all data at runtime can be stored in the activation records on a stack.

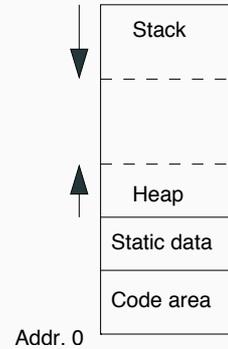
### More general language features

Global variables, nested procedures, linked structures and pointers, classes, ..., have other requirements: a stack is not sufficient for runtime memory management.

## Memory organisation



### Typical memory organisation



### Comments

- Static area for global variables
- Stack and heap grow from opposite ends to avoid predetermined size decisions
- Stack managed by LLVM
- Management of heap much more complicated than stack

## Arrays in JVALETTE



### Java-like arrays

Arrays in the JVALETTE extensions are similar to Java arrays:

- A variable of type e.g. `int[]` contains a reference to a block of memory on the heap, where array elements are stored.
- Arrays must be explicitly created as in  
`int[] v = new int[20];`
- Lower bound of array index is always 0
- Array elements are initialized to `0/0.0/false`
- Arrays have a `length` attribute, with dot-notation
- Arrays can be both function arguments and results

## Two extensions (each one credit)



### First extension

One-dimensional arrays and 'foreach' statement, as in

```
int sum = 0;
for (int x : v)
    sum = sum + x;
```

The ordinary `for` statement is not required.

## Two extensions (each one credit)



### First extension

One-dimensional arrays and 'foreach' statement, as in

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### Second extension

Multidimensional arrays:

- All indices must get upper bounds when an array is created
- For  $n > 1$ , an  $n$ -dimensional array is a one-dimensional array, each of whose elements is an  $n - 1$ -dimensional array

## Sample LLVM code



### Indexing in two-dimensional array

```
%arr1 = type %struct1*
%arr2 = type %struct2*
%struct1 = type {i32, [0 x i32]}
%struct2 = type {i32, [0 x %arr1]}

define i32 @getElem (%arr2 %m, i32 %i, i32 %j) {
    %p1 = getelementptr %struct2, %arr2 %m,
        i32 0, i32 1, i32 %i
    %p2 = load %arr1, %arr1* %p1
    %p3 = getelementptr %struct1, %arr1 %p2,
        i32 0, i32 1, i32 %j
    %p4 = load i32, i32* %p3
    ret i32 %p4
}
```

Your generated code may well look different.

## Hints for array extension



### First extension

- LLVM type of array hinted at in previous slide, use size 0
- Use C function `calloc` to allocate 0-initialized memory
- New forms of expression: array indexing and `new` expression
- Indexed expressions also as L-values in assignments
- Not required to generate bounds-checking code

### Second extension

## Hints for array extension



### First extension

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### Second extension

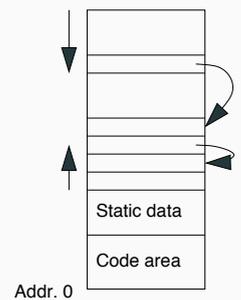
- `new` expression with several indices involves generating code with loops and repeated `calloc`'s
- Indexing requires several `getElementptr` instructions

## Structures and pointers

## Structures and pointers extension



- In addition to function definitions, a Javalette file may contain definitions of structures and pointer types
- Structure objects are allocated on the heap, using `new`
- Pointer variable (on stack) may refer to memory structure on the heap



## Structures and pointers examples



Code examples in JAVALETTE.

```
typedef struct Node *list;

struct Node {
  int elem;
  list next;
}

list cons(int x, list xs) {
  list res;
  res = new Node;
  res->elem = x;
  res->next = xs;
  return res;
}
```

```
int length(list xs) {
  if (xs == (list)null)
    return 0;
  else
    return 1 + length(xs->next);
}

list fromTo(int m, int n) {
  if (m > n)
    return (list)null;
  else
    return cons(m, fromTo(m + 1, n));
}
```

## Adding structures and pointers to JAVALETTE



### New toplevel definitions

- Structure definitions, exemplified by `Node`
- Pointer type definitions, exemplified by `list`

### New expression forms

### New statement forms

## Adding structures and pointers to JVALETTE



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- Structure definitions, exemplified by `Node`
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### New expression forms

- Heap object creation, exemplified by `new Node`
- Pointer dereferencing, exemplified by `xs->next`
- Null pointers, exemplified by `(list)null`

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## Adding structures and pointers to JVALETTE



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- Structure definitions, exemplified by `Node`
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### New expression forms

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- Null pointers, exemplified by `(list)null`

### New statement forms

- Pointer dereferencing allowed in left hand sides of assignments, as in `xs->elem = 3;`
- In absence of garbage collection, you should have a `free` statement

## Implementing structures and pointers in LLVM backend



### Some hints

- Structure and pointer type definitions translate to LLVM type definitions
- Again, use `calloc` for allocating heap memory
- `getelementptr` and `load` will be used for pointer dereferencing
- Info about struct layout may be needed in the state of code generator

## Implementing structures and pointers in LLVM backend



### Some hints

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### From previous lecture: Computing the size of a type

We use the `getelementptr` instruction:

```
%p = getelementptr %T, %T* null, i32 1
%s = ptrtoint %T* %p to i32
```

Now, `%s` holds the size of `%T`.

## Other uses of pointers (not part of extension)



### Code example (in C)

```
void swap (int *x, int *y) {
    int tmp = *x;
    *x = *y;
    *y = tmp;
}

int main () {
    int a = 1;
    int b = 3;
    swap(&a, &b);
    printf("a=%d\n", a);
}
```

## Other uses of pointers (not part of extension)



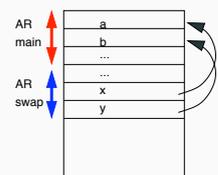
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    printf("a=%d\n", a);
}
```

### Parameter passing by reference

- To make it possible to return results in parameters, one may use pointer parameters
- Actual arguments are addresses
- Problem: makes code optimization much more difficult



## Call by reference and aliasing



### Code examples

```
void swap (int *x, int *y) {  
    int tmp = *x;  
    *x = *y;  
    *y = tmp;  
}
```

```
...  
swap (x, x);  
...
```

## Call by reference and aliasing



### Code examples

```
void swap (int *x, int *y) {  
    int tmp = *x;  
    *x = *y;  
    *y = tmp;  
}
```

```
...  
swap (x, x);  
...
```

### Comments

- With call by reference and pointers, two different variables may refer to the same location; aliasing
- Aliasing complicates code optimization:  
    x := 2  
    y := 5  
    a := x + 3  
Here we might want to replace last instr by a := 5; but what if y is an alias for x?

## Deallocating heap memory



### The problem

In contrast to stack memory, there is no simple way to say when heap allocated memory is not needed anymore.

### Two main approaches

1. Explicit deallocation
  - Programmer deallocates memory when no longer needed (using `free`)
  - Potentially most efficient
  - Very easy to get wrong (memory leakage or premature returns)
2. Garbage collection
  - Programmer does nothing; runtime system reclaims unneeded memory
  - Secure but runtime penalty
  - Acceptable in most situations
  - Used in Java, Haskell, C#, ...

## Garbage collection



### General approach

Runtime system keeps list(s) of free heap memory, `malloc` returns a chunk from suitable free list.

Many variations. Some approaches:

1. Reference counting: each chunk keeps a reference count of incoming pointers, when count becomes zero, chunk is returned to free list; problem: cyclic structures
2. When free list is empty, collect in two phases:
  - Mark** Follow pointers from global and local variables, marking reachable chunks
  - Sweep** Traverse heap and return unmarked chunks to free list

## Object-orientation

## Object-oriented languages



### Class-based languages

We consider only languages where objects are created as instances of classes. A class describes:

- a collection of instance variables; each object gets its own copy of this collection
- a collection of methods to access and update the instance variables

Each object contains, in addition to the instance variables, a pointer to a class descriptor. This descriptor contains addresses of the code of methods.

Without inheritance, all this is straightforward; classes are just structures. We propose a little bit more: single inheritance without method override.

## JVALETTE classes, code example 1



```
class Counter {
    int val;

    void incr () {
        val++;
        return;
    }

    int value () {
        return val;
    }
}
```

```
int main () {
    Counter c;
    c = new Counter;
    c.incr();
    c.incr();
    c.incr();
    int x = c.value();
    printInt(x);
    return 0;
}
```

## JVALETTE classes, code example 2



```
class Point2 {
    int x;
    int y;

    void move(int dx, int dy) {
        x = x + dx;
        y = y + dy;
    }

    int getX() { return x; }

    int getY() { return y; }
}
```

```
class Point3 extends Point2 {
    int z;
    void moveZ(int dz) {
        z = z + dz;
    }
    int getZ() { return z; }
}

int main() {
    Point2 p;
    Point3 q = new Point3;

    q.move(2, 4);
    q.moveZ(7);
    p = q;
    ...
}
```

## Adding classes to basic JVALETTE (extension 1)



### New toplevel definitions

- Class definitions, consisting of a number of instance variable declarations and a number of method definitions
- Instance variables are only visible within methods of the class
- All methods are public
- All classes have one default constructor, which initializes instance variables to default values (0, false, null)
- A class may extend another one, adding more instance variables and methods, but without overriding
- Classes are types; variables can be declared to be references to objects of a class
- We have subtyping; if S extends C, then S is a subtype of C; whenever an object of type C is expected, we may supply an object of type S.

## Hints for object extension 1



### New forms of expressions

- Object creation, exemplified by `new Point2`, which allocates a new object on the heap with default values for instance variables
- Method calls, exemplified by `p.move(3,5)`
- Null references, exemplified by `(Point)null`
- Self reference. Within a class, `self` refers to the current object; all calls to sibling methods within a class must use method calls to `self`

### Implementation hints

Much of ideas (and code) from the pointers/structures extension can be reused.

Method calls will be translated to function call with receiving object as extra, first parameter.

## Overriding / dynamic dispatch (extension 2)



### Example with overriding

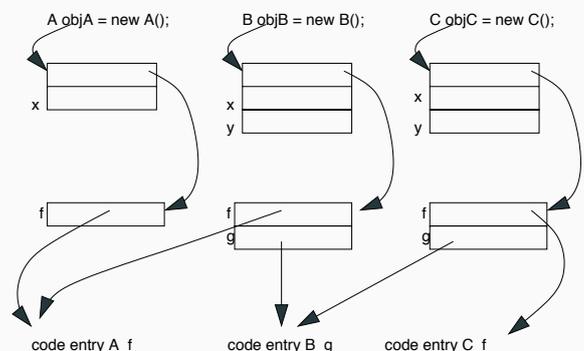
We consider the following classes:

```
class A {
    int x;
    void f (int z) {x = z;}
}

class B extends A {
    int y;
    int g() {return 0;}
}

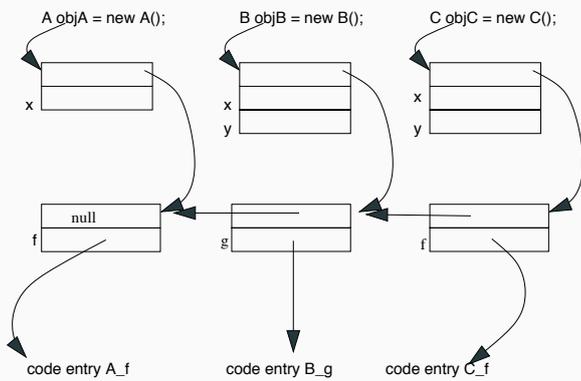
class C extends B {
    void f(int z) {x = z; y = 0;}
}
```

## Objects at runtime



Each object includes instance variables and pointer to class descriptor.

## Objects at runtime, variant



Class descriptors linked into list. List searched at runtime.

## Dynamic dispatch



### Code example

```
A obj = objA;  
...  
obj.f(5);  
...  
obj = objC;  
...  
obj.f(3);
```

## Dynamic dispatch



### Code example

```
A obj = objA;  
...  
obj.f(5);  
...  
obj = objC;  
...  
obj.f(3);
```

### What code is run?

- The method to execute is determined at runtime by following the link to the class descriptor
- Static type checking guarantees that there is a method with proper signature in the descriptor
- There is an efficiency penalty in dynamic dispatch (so optimization tries to remove it)

## Modules

## Module systems



### Programmer's perspective: Modularity

- Reusability
- Information hiding
- Name space control

## Module systems



### Programmer's perspective: Modularity

- Reusability
- Information hiding
- Name space control

### Compiler's perspective: Separate compilation

- Smaller compilation units
- Recompilation only of changed units
- Library modules released as binaries

## Some approaches



### Increasing levels of sophistication

- Inclusion mechanism: concatenate all files before compilation
- Include with header files: headers with type information included for compilation and separate linking
- Import mechanism:
  - Compilation requires interface info from imported files
  - Compilation generates interface and object files
  - Often in OO languages, module = class

## A possible module system for basic JAVALETTE



### Extension proposal

- One module per file
- All modules in same directory (further extension: define search path mechanism)

### Observations

- Mainly system for name space control and libraries
- If you want to implement it, you may get credits
- Difficulty: not much support in LLVM

## Import in JAVALETTE



### New syntax

If  $M$  is a module name, then

- `import M` is a new form of declaration
- `M.f(e1, ..., en)` is a new form of expression

### Unqualified use

A function in an imported module may be used without the module qualification if the name is unique. Name clashes are resolved as follows:

- If two imported modules define a function  $f$ , we must use the qualified form
- If the current module and an imported module both define  $f$ , the unqualified name refers to the local function

## Import and dependency



### Import

To use functions defined in  $M$ , another module must explicitly import  $M$ .

Hence, import is not transitive, i.e, if  $M$  imports  $L$  and  $L$  imports  $K$ , it does not follow that  $M$  imports  $K$ .

### Dependency

- If  $M$  imports  $L$ , then  $M$  depends on  $L$
- If  $M$  imports  $L$  and  $L$  depends on  $K$ , then  $M$  depends on  $K$ ; dependency is transitive

We assume that dependency is non-cyclic: if  $M$  depends on  $N$ , then  $N$  may not depend on  $M$ .

## Compiling a module, 1



### Compiler's tasks

When called by `jl c M.jl`, the compiler must

1. Read the import statements of  $M$  to get list of imported modules
2. Recursively, read the import statements of these modules (and report an error if some module not found)
3. Build dependency graph of involved modules
4. Sort modules topologically (and report error if cyclic import found)
5. Go through modules in topological order ( $M$  last) and check timestamps to see if recompilation is necessary

Hint: It is OK to require that import statements are in the beginning of the file and with one import per line to avoid need of complete parsing.

## Compiling a module, 2



### Symbol table

You need a symbol table with types of functions from all imported modules. This info is readily available in LLVM files, but needs to be collected (and parsed).

Build the symbol table so that unqualified names will find the correct type signature (i.e., you must check for name clashes).

**Note 1** It is a good idea to replace unqualified names by qualified (for code generation)

**Note 2** Type declaration for all imported functions must be added to LLVM file