Compiler Design

Lecture 22: Summary

Christophe Dubach

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Summary

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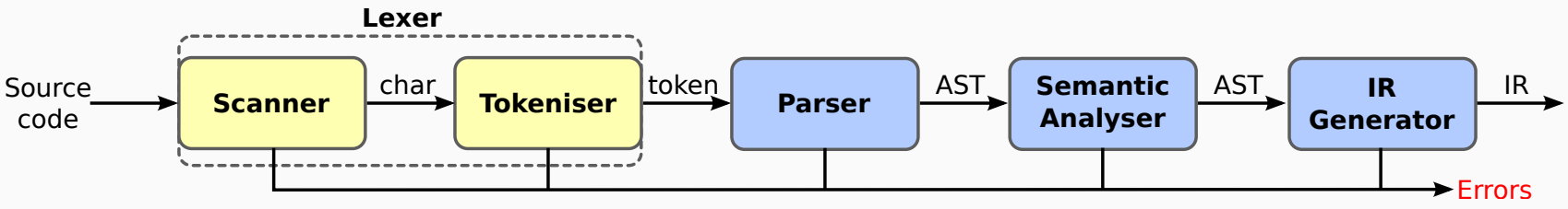
The Lexer



- Maps character stream into words/tokens
- Typical tokens: number, identifier, `+`, `-`, `new`, `while`, `if`, ...
- Assign a syntactic category to each token:
  - $x = x + y$; becomes ID(x) EQ ID(x) PLUS ID(y) SC

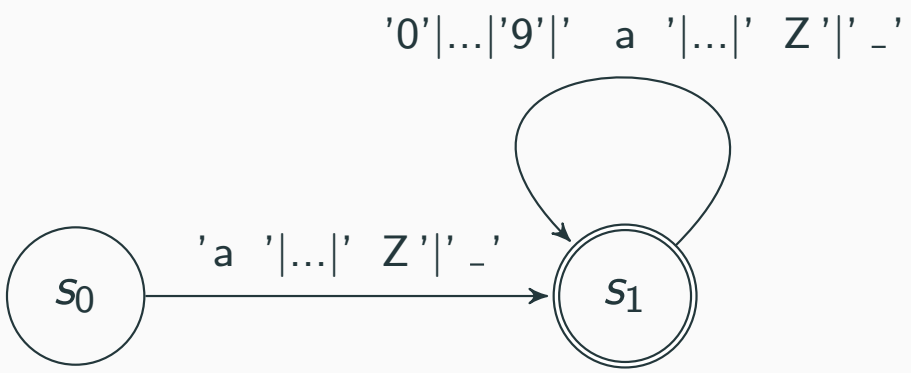
Typically, tokens are described using regular expressions.

Example

```
IDENTIFIER ::= ('a'|...|'Z'|'_')('0'|...|'9'|'a'|...|'Z'|'_')*
```

Automatic Lexer Generation

The Regular Expression corresponds to a finite state automata:



It is possible to systematically generate a lexer for any regular expression.

This can be done in three steps:

1. regular expression (RE) $\rightarrow$ non-deterministic finite automata (NFA)
2. NFA $\rightarrow$ deterministic finite automata (DFA)
3. DFA $\rightarrow$ generated lexer

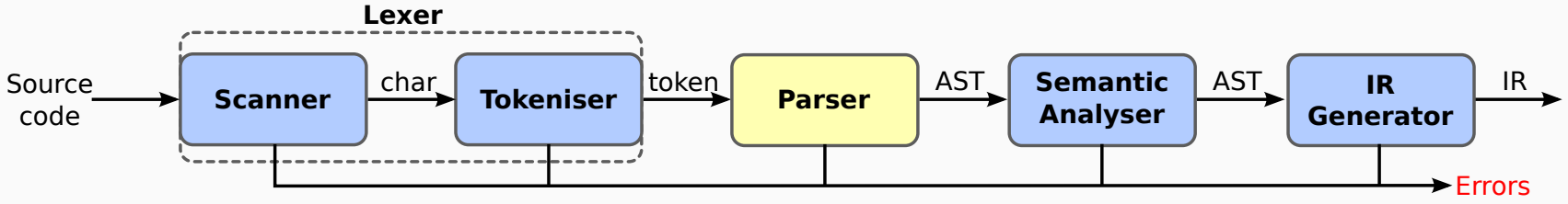
Table encoding

	'a'|...|'Z'|'_'	'0'|...|'9'	other
s_0	s_1	error	error
s_1	s_1	s_1	end

Skeleton recogniser

```
c = next character
state = s0
while(c ≠ EOF)
  state = δ(state, c)
  c = next character
if (state final)
  return success
else
  return error
```

The Parser



- Checks grammatical correctness of the stream of words/tokens produced by the lexer
- Outputs the AST (Abstract Syntax Tree) which represents the input program

Writing a recursive descent parser:

1. Express the language syntax as an LL(k) CFG;
2. Encode precendence'
3. Left factorize the grammar if necessary;
4. Remove left recursion from the grammar if present;
5. Write the recursive parser using at most `k` lookaheads.

LL(k) grammar

- Left-to-Right parsing;
- Leftmost derivation; (i.e. apply production for leftmost non-terminal first)
- Only k symbols of lookahead to make decision.

Your parser will never have to backtrack!
$\Rightarrow O(N)$ time complexity

Top-Down vs. Bottom-Up Parsers

Top-Down Parser

A Top-Down parser builds a derivation by working from the start symbol to the input sentence.

Bottom-Up Parser

A Bottom-Up parser builds a derivation by working from the input sentence back to the start symbol.

Leftmost vs Rightmost derivation

Example: CFG

Goal ::= a A B e

A ::= A b c | b

B ::= d

Leftmost derivation

Goal

aABe

aAbcBe

abbcBe

abbcde

Rightmost derivation

Goal

aABe

aAde

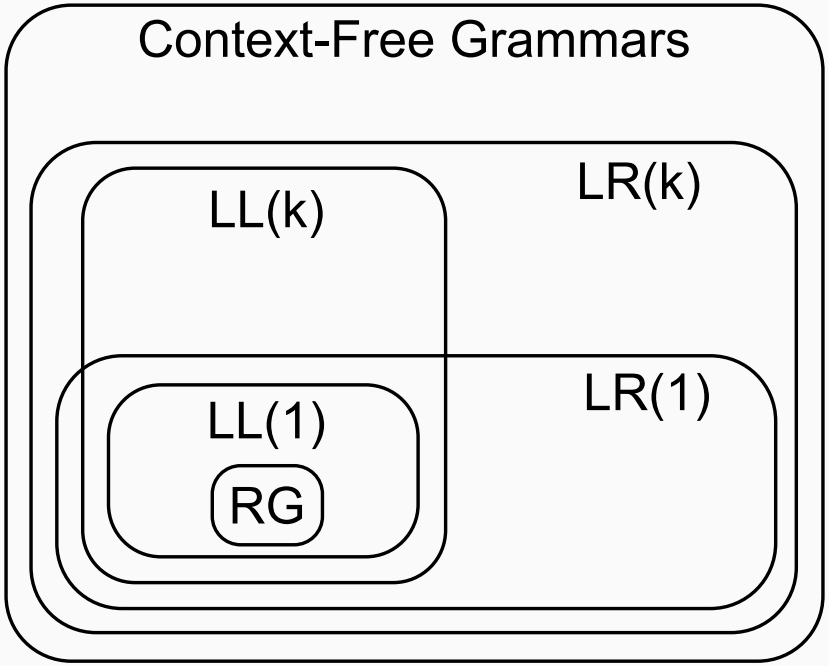
aAbcde

abbcde

LL parsers

LR parsers

Expressive Power of Grammars



LL grammars subset of LK grammar since they cannot be left-recursive!

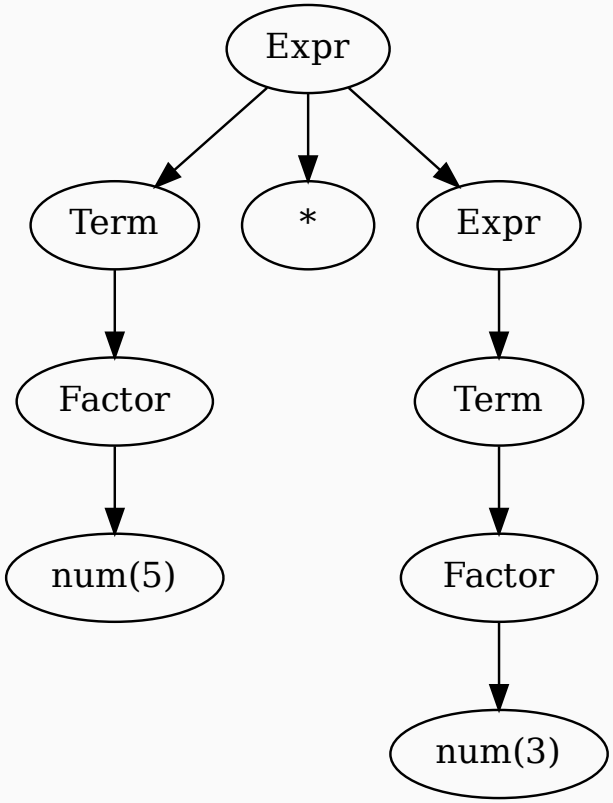
Summary

Concrete Syntax Tree (Parse Tree)

CFG for arithmetic expressions

```
Expr     ::= Term (('+' | '-') Expr | ϵ)
Term     ::= Factor (('*'|'/') Term | ϵ)
Factor   ::= number | id | '(' Expr ')'
```

Concrete Syntax Tree for $5 * 3$



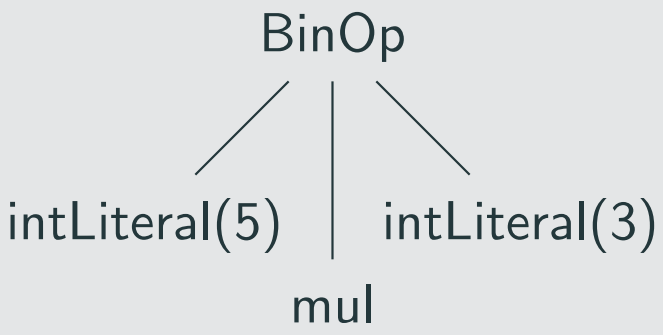
The concrete syntax tree contains a lot of unnecessary information.

Abstract Grammar

Example: abstract grammar for arithmetic expressions

```
Expr  ::= BinOp | intLiteral | id
BinOp ::= Expr Op Expr
Op    ::= add | sub | mul | div
```

$5 * 3$



This is the Abstract Syntax Tree

AST Processing / Compiler Pass with visitor

When pattern matching not availbe in the host programming language, using visitor design pattern to implement double-dispatch mechanism.

Visitor Interface

```
interface Visitor<T> {
  T visitIntLiteral(IntLiteral il);
  T visitBinOp(BinOp bo); }
```

AST classes

```
abstract class Expr {
  abstract <T> T accept(Visitor<T> v);
}
class IntLiteral extends Expr {
  ...
  <T> T accept(Visitor<T> v) {
    return v.visitIntLiteral(this);
} }
class BinOp extends Expr {
  ...
  <T> T accept(Visitor<T> v) {
    return v.visitBinOp(this);
} } }
```

Name Analysis

Link variable uses and function calls to their declaration.

```
int i;
int j;
void foo() {...};
void main(int i) {
  int j;
  i;
  {
    int j;
    j;
  }
  j;
  foo();
}
```

Use symbol table and scope information to track identifiers.

Type Analysis

Different languages, different approaches

	strong	**weak**
static	Java	C/C++
dynamic	Python	JavaScript

Use typing rules to formalize. For instance:

$$\textsc{IntLit}\ \frac{}{\vdash i : \textbf{int}} \qquad \textsc{BinOp}\ \frac{\vdash e_1 : \textbf{int} \qquad \vdash e_2 : \textbf{int}}{\vdash e_1 + e_2 : \textbf{int}}$$

Traverse the AST depth-first, post-order, to assign a type to every expression.

Summary

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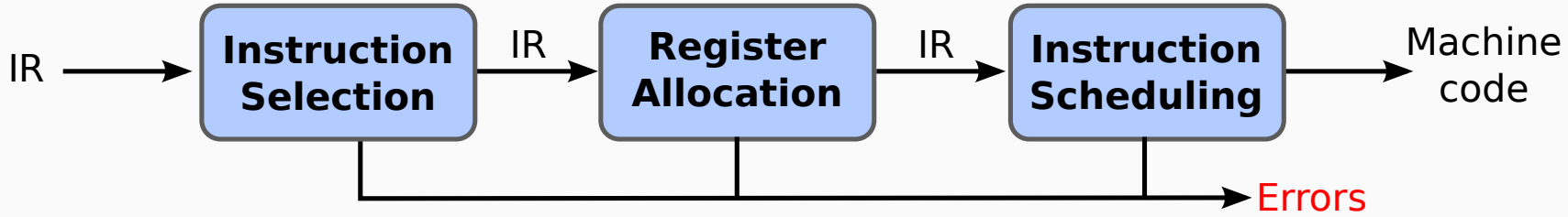
The Back end



- Translate IR into target machine code (or something resembling it);
- Choose instructions to implement each IR operation;
- Decide which value to keep in registers.

Code Generation

To simplify, use virtual registers and convert to arch. registers later.

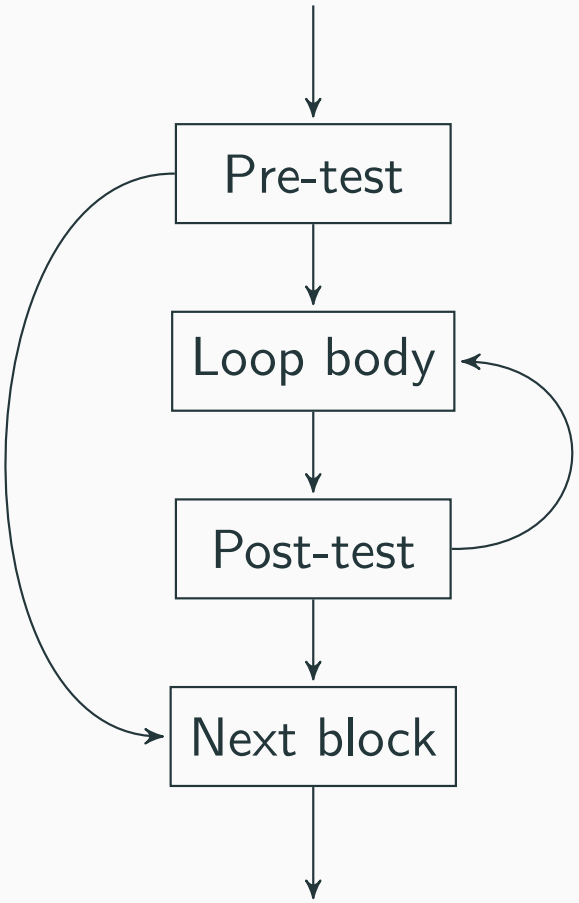
Simple AST traversal:

```
Register visitBinOp(BinOp bo) {
  Register lhsReg = bo.lhs.accept(this);
  Register rhsReg = bo.rhs.accept(this);
  Register resReg = newVirtualRegister();
  switch(bo.op) {
    case ADD:
      emit("add", resReg, lhsReg, rhsReg);
      break;
    case MUL:
      emit("mult", lhsReg, rhsReg);
      emit("mflo", resReg);
      break;
    ...
  }
  return resReg;
}
```

Control-Flow structures

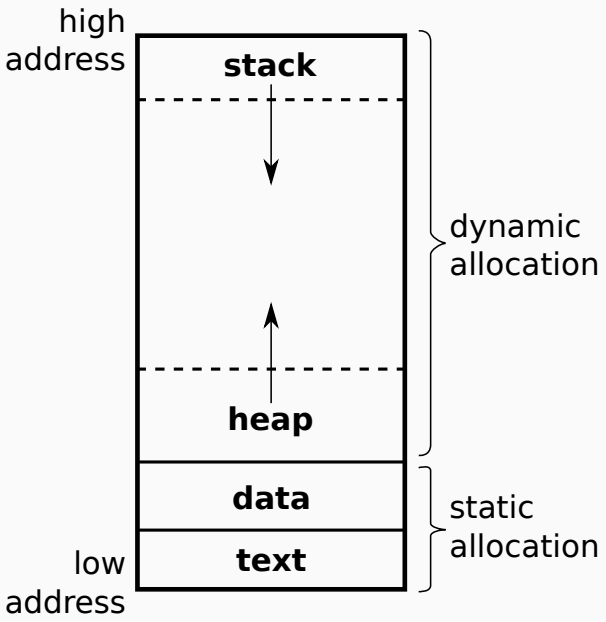
- loops;
- logical operators (short-circuit evaluation);
- if-then-else.

Use simple code pattern / shapes and emits labels:



Memory allocation

A compiler keeps track of where variables are allocated, and allocate each of them.



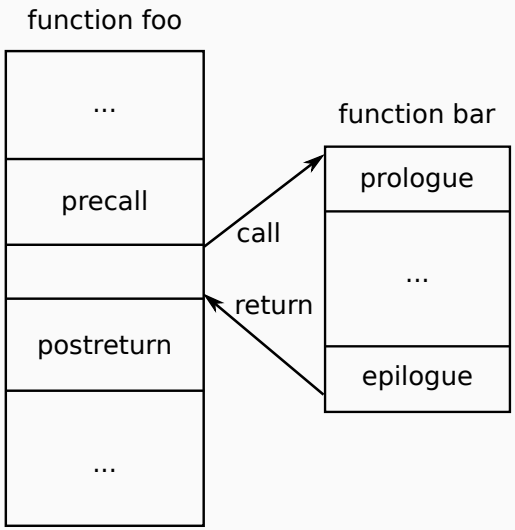

```
char c;                    static
int arr[4];                static
void foo() {
  int arr2[3];             stack
  int* ptr =               stack/register
    (int*)malloc(sizeof(int)*2);  heap
  ...
  {
     int b;                stack/register
     ...
     bar("hello");         static
  }
  ...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

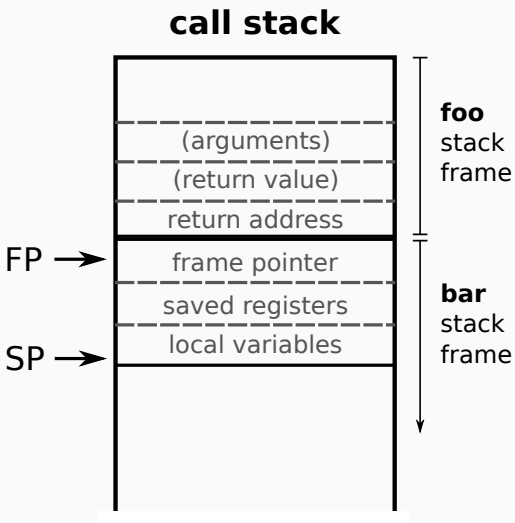
Dealing with function calls

Things can get quite complex when dealing with function call:

- The compiler must manage the `$sp` and `$fp` correctly;
- Save the registers used by the function on the stack;
- As well as the stack pointer and frame pointer.
- Some arguments must be copied while others are passed by reference.

All this of course depends on the language and the target machine!





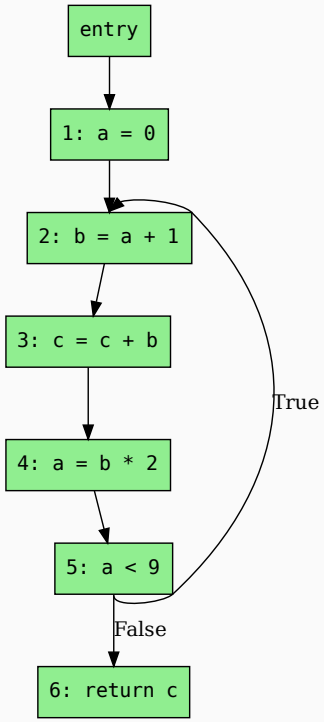
Summary

Register allocation in a nutshell

1. Pseudo-assembly:

```
    a = 0
L1: b = a + 1
    c = c + b
    a = b*2
    if (a<9) goto L1
    return c
```

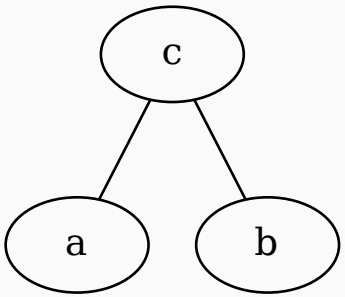
2. Control flow graph:



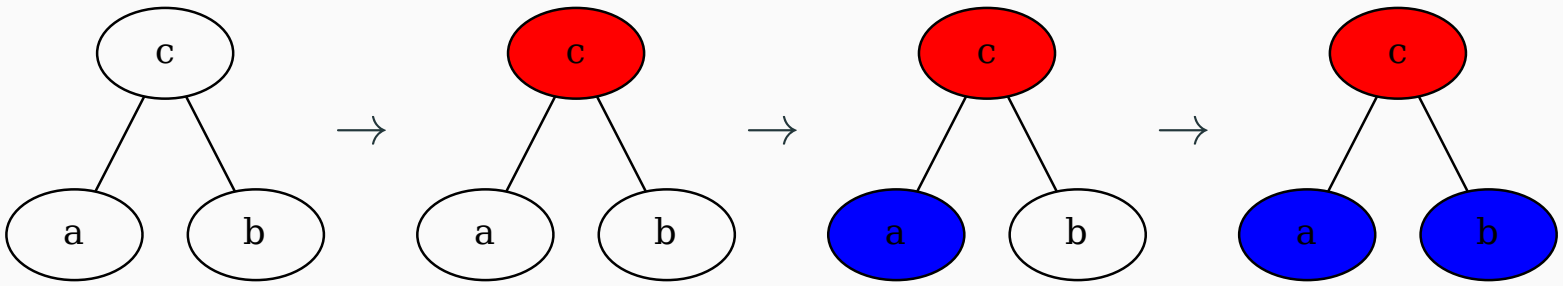
3. Liveness:

node	out	in
6		c
5	ac	ac
4	ac	bc
3	bc	bc
2	bc	ac
1	ac	c

4. Interference graph:



5. Graph colouring:



6. Virtual to architectural registers

Possible mapping:

- a → $t0
- b → $t0
- c → $t1

(pseudo-)assembly final code:

```
    $t0 = 0
L1: $t0 = $t0 + 1
    $t1 = $t1 + $t0
    $t0 = $t0*2
    if ($t0<9) goto L1
    return $t1
```

Use Chaitin algorihtm for graph colouring.

Register allocation challenges

- Graph colouring can be slow:
  - Production compilers prefer other techniques such as linear scan.
- When it is not possible to colour the graph, need to spill:
  - this is what is crucial for producing good quality code;
  - a bit of a dark art.

Summary

Instruction selection

Goal: produce "smarter" code by exploiting instruction set.

Peephole matcher

Steps of the Simplifier (*3-operation window*)

LLIR Code

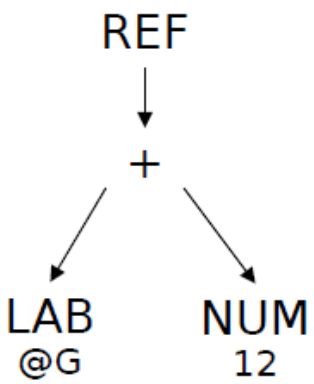
$r_{10} \leftarrow 2$
$r_{11} \leftarrow @y$
$r_{12} \leftarrow r_0 + r_{11}$
$r_{13} \leftarrow \text{MEM}(r_{12})$
$r_{14} \leftarrow r_{10} \times r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow r_0 + r_{15}$
$r_{17} \leftarrow \text{MEM}(r_{16})$
$r_{18} \leftarrow r_{17} - r_{14}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow r_0 + r_{19}$
$\text{MEM}(r_{20}) \leftarrow r_{18}$

$r_{10} \leftarrow 2$
$r_{12} \leftarrow r_0 + @y$
$r_{13} \leftarrow \text{MEM}(r_{12})$

→

$r_{10} \leftarrow 2$
$r_{13} \leftarrow \text{MEM}(r_0 + @y)$
$r_{14} \leftarrow r_{10} \times r_{13}$

Tree Pattern-Matcher



Sequences with Cost of 2	
6: Reg → LAB_1 11: Reg → REF(+(Reg_1,NUM_2))	`loadI @G` ⇒ r_i `loadAI` r_i`,12` ⇒ r_j
8: Reg → NUM_1 14: Reg → REF(+(LAB_1,Reg_2))	`loadI 12` ⇒ r_i `loadAI` r_i`,@G` ⇒ r_j

Summary

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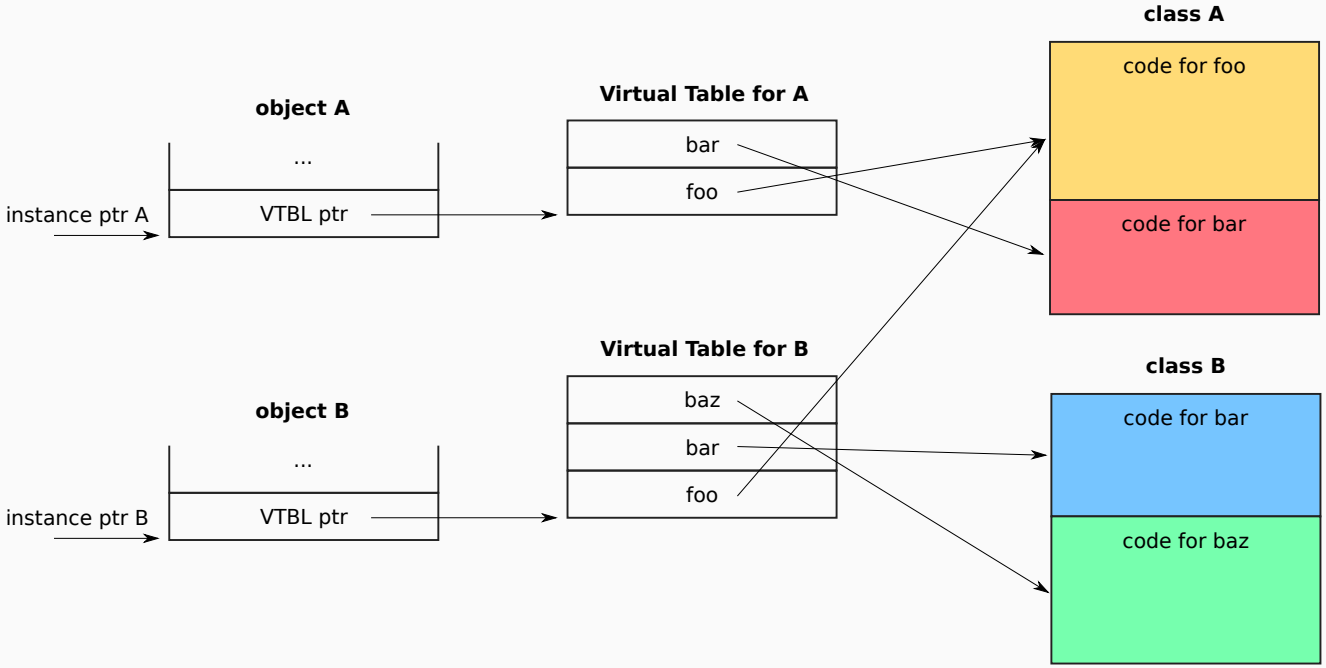
Singe inheritance

Easy to support:

- Layout fields from superclass sequentially;
- Use a single virtual table.

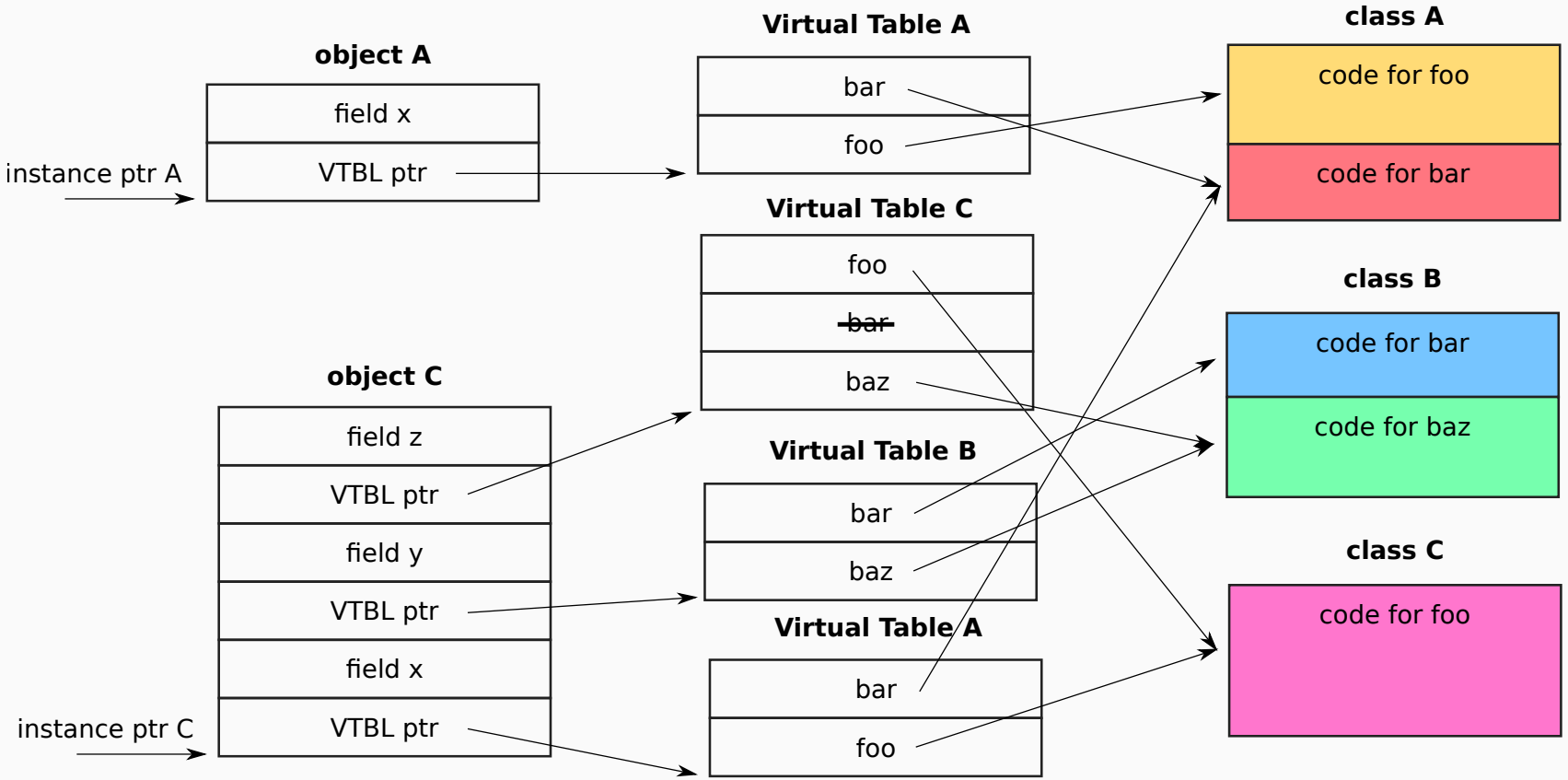
```
class A {
 void foo(){print("foo_a")}
 void bar()(prinf("bar_a")}
 }
```

```
class B extends A {
 void bar(){print("bar_b")}
 void baz(){print("baz_b")}
}
```



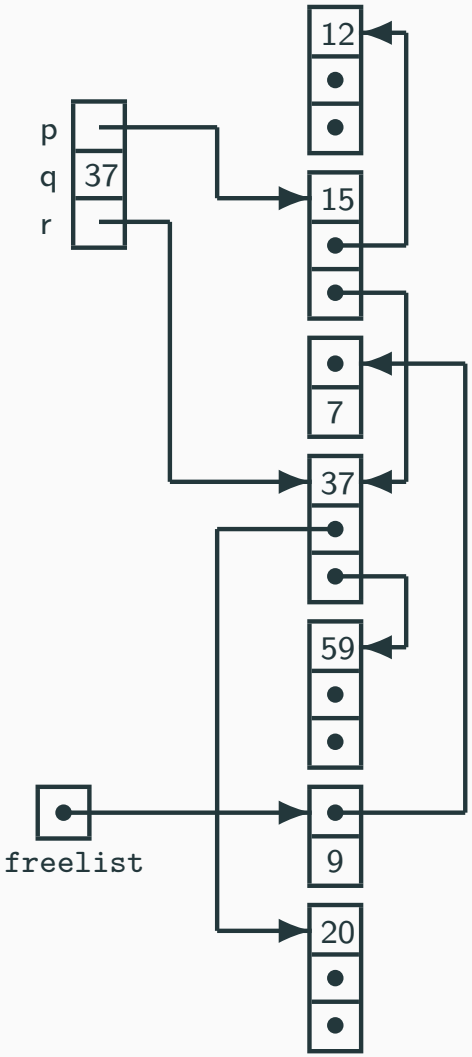
Multiple inheritance

Much more complex to handle. Need to embed the superclass object layout and use multiple virtual tables.



Summary

Garbage Collection



Goal: find objects/records that can never be reached.

Three main approaches:

- Reference counting;
- Mark and sweep;
- Stop and copy;

Stop-and-Copy, with a generational collection is pretty good.

Summary

What's next?

In this course, we have only scratched the surface of the world of compilers. Compilation is still a very active research field and there is plenty of development.

If you want to gain experience with industry compilers:

- For C like languages: LLVM
- For Java like languages: GraalVM / Truffle (from Oracle Labs)
- For JavaScript: V8

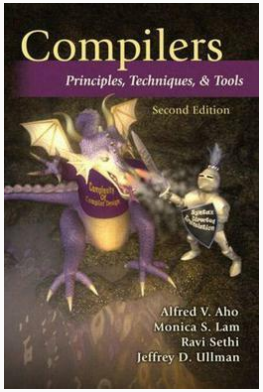
Hot compiler IRs:

- MLIR (connected to LLVM)
- WebAssembly (virtual assembly for the web)

Courses you may also like:

- COMP 764 : "High-Level Hardware Synthesis" (TBD, Winter 2022)
- ECSE 427 / COMP 310 : Operating Systems
- COMP 409 : Concurrent Programming

What to read next:



The "Dragon book":
Compilers: Principles, Techniques, and Tools
Alfred Aho*, Monica Lam, Ravi Sethi, Jeffrey Ullman*
*ACM Turing Award Winners, 2021

Research in my group (COMP 400, ECSE 498, SURE/SURA)

- Parallel programming abstractions based on Lambda calculus
- Rewrite-based optimizations
- High performance code generation
- High-level hardware synthesis

Looking for job/internship related to compilation?

- https://github.com/mgaudet/CompilerJobs

The end