G53CMP: Lecture 11

Code Generation I

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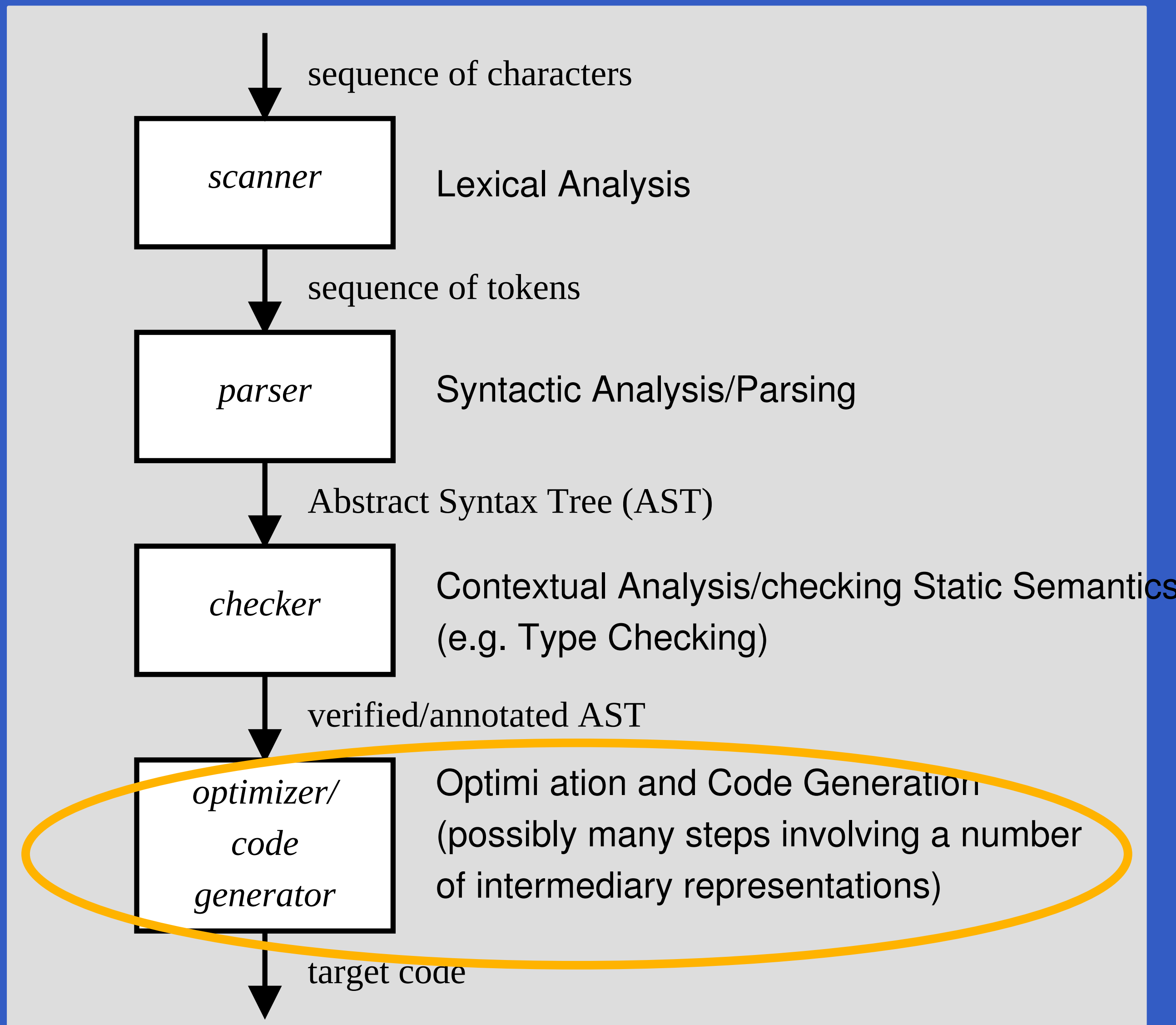
Where Are We?


sequence of characters
scanner
Lexical Analysis
sequence of tokens
parser
Syntactic Analysis/Parsing
Abstract Syntax Tree (AST)
checker
Contextual Analysis/checking Static Semantics
(e.g. Type Checking)
verified/annotated AST
optimizer/
code
generator
Optimi ation and Code Generation
(possibly many steps involving a number
of intermediary representations)
target code

Code Generation: Subproblems (1)

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- ***Code Selection***: Which code sequence to generate for each source code phrase? For example, for an expression (phrase) like

```
y := 3 + x * 5
```

  the code for a register machine might be:

```
MUL R7, R1, #5
ADD R2, R7, #3
```

Code Generation: Subproblems (2)

- ***Storage Allocation***: Where and how to store data? E.g.
  - Global variables
  - Local variables

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- ***Storage Allocation***: Where and how to store data? E.g.
  - Global variables
  - Local variables
- ***Register Allocation***: How to allocate registers for variables and other purposes?

Run-Time Organisation (1)

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Code generation is intimately related to the ***Run-Time Organisation***. This includes:

- ***Memory Organisation***: How to organise the memory into data structures for different kinds of storage; e.g.
  - Global static storage
  - Stacks
  - Heaps

Run-Time Organisation (2)

- ***Calling conventions***: protocols for procedure/function/method calls and returns, including how to
  - pass arguments
  - return results

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- ***Calling conventions***: protocols for procedure/function/method calls and returns, including how to
  - pass arguments
  - return results
- ***Data Representation***: How to represent high-level data types (integers, records, arrays, objects, . . .) as sequences of bits?

This Lecture

- Code selection
- Specifically, code selection for the Triangle Abstract Machine (TAM), a ***stack machine***.
- Stack machines:
  - simplify code selection
  - allow us to defer a more in-depth treatment of run-time organisation until later
  - but we will cover the basics of TAM calling conventions

The Triangle Abstract Machine (1)

Watt & Brown use the ***Triangle Abstract Machine*** (TAM) to illustrate code generation. We will use a variant.

- TAM is a simple ***stack machine***.
- Dedicated registers define the stack: `ST`, `LB`, `SB`.
- Operands and results for all instructions on the stack.
- Register allocation is thus a non-issue.

The Triangle Abstract Machine (2)

Stack machines in perspective:

- Hardware CPUs (e.g. x86, SPARC, ARM) tend to be ***register machines***, not stack machines.
- Code for a stack machine thus has to be either
  - interpreted
  - compiled further
- The Java Virtual Machine (JVM) is a prominent, real-world example of a stack machine.
- JVM code is typically Just-In-Time (JIT) compiled for execution speed.

TAM Registers

The TAM has a number of registers related to the stack. Among others:

- ***SB***: Stack Base
- ***ST***: Stack Top
- ***LB***: Local Base

TAM Instructions (1)

- `LOADL` c: push constant c onto stack.
- `LOADA` a: push *address* a onto stack.
  Address a can be e.g. [SB + d] or [LB + d].
- `LOAD` a: push *contents* at address a onto stack.
  Address a can be e.g. [SB + d] or [LB + d].
- `STORE` a: pop value from stack and store at address a.
- `LOADI` d and `STOREI` d: *indirect* load and store; target address $=$ top stack elem. $+ d$.
- `POP` m n: pop n values below the top m values off the stack.

TAM Instructions (2)

- `LOAD [SB + d]`: fetch the value of the (global) variable at address `d` relative to `SB`.
- `STORE [SB + d]`: store a value in the (global) variable at address `d` relative to `SB`.
- `LOAD [LB + d]`: fetch the value of the (local) variable at address `d` relative to `LB`.
- `STORE [LB + d]`: store a value in the (local) variable at address `d` relative to `LB`.

Displacements may also be negative; e.g. `LOAD [SB - d]` etc.

Addressing relative to `ST` also possible.

TAM Instructions (3)

- `JUMP` l: jump unconditionally to label l.
- `JUMPIFZ` l: pop value on top of stack, jump to label l if it is 0.
- `JUMPIFNZ` l: pop value on top of stack, jump to label l if it is not 0.
- `CALL` f: call function at label f, arguments and result on stack.
- `RETURN` m n: return to caller from routine with n arguments with the m top stack locations replacing the activation record.

TAM Instructions (4)

All of the following take argument(s) from the stack and leave the result on the stack:

- Arithmetic: `ADD`, `SUB`, `MUL`, `DIV`, `NEG`
- Comparison: `LSS`, `EQL`, `GTR`
- Logical: `AND`, `OR`, `NOT`

(There are also subroutines for these operations (and more) in the MiniTriangle standard library. E.g. `CALL mul` is an alternative to `MUL`. This allows for a uniform treatment of functions, facilitating code generation.)

Example: TAM Code Selection

Example of code selection for TAM:

```
x := x * 2
```

TAM code, assuming `x` stored at `[SB + 1]`:

```
LOAD [SB + 1]
LOADL 2
MUL
STORE [SB + 1]
```

Let's do a live demo . . .

Exercise: TAM Code Selection

Assuming the variable

- `x` is stored at address `[SB + 1]`
- `y` is stored at address `[SB + 2]`

write code for

```
x := y; y := 17
```

and

```
repeat
    y := y + x;
    x := x + 1
until x == 10
```

TAM Calling Conventions (1)

```
var n: Integer;
...
fun f(x,y: Integer): Integer =
    let
        z: Integer
    in begin
        z := x * x + y * y;
        return n * z
    end
```

(Not quite current MiniTriangle as function body must be an expression.)

TAM Calling Conventions (2)

TAM activation record layout:

address	contents
LB $-$ $argOffset$	arguments
...	...
LB	static link
LB + 1	dynamic link
LB + 2	return address
LB + 3	local variables
...	...
LB + $tempOffset$	temporary storage

where

$$argOffset = \mathrm{size}(arguments)$$

$$tempOffset = 3 + \mathrm{size}(local\ variables)$$

TAM Calling Conventions (3)

TAM code for the example:

```
LOADL 0          ; z       ADD
LOAD  [LB - 2]; x          STORE   [LB + 3] ; z
LOAD  [LB - 2]; x          LOAD    [SB + 42]; n
MUL                        LOAD    [LB + 3] ; z
LOAD  [LB - 1]; y          MUL
LOAD  [LB - 1]; y          POP     1 1
MUL                        RETURN  1 2
```

Note: all offsets are in ***words*** (4 bytes).

Execution of the Example (1)

On entry:

address	contents
...	...
SB + 42	n: n
...	...
LB - 2	x: x
LB - 1	y: y
LB	static link
LB + 1	dynamic link
LB + 2	return address
ST	

Execution of the Example (2)

After `LOADL 0`:

address	contents
...	...
SB + 42	n: n
...	...
LB − 2	x: x
LB − 1	y: y
LB	static link
LB + 1	dynamic link
LB + 2	return address
LB + 3	z: *uninitialized*
ST	

Execution of the Example (3)

After `LOAD [LB - 2]; LOAD [LB - 2]`:

address	contents
...	...
SB + 42	n: n
...	...
LB - 2	x: x
LB - 1	y: y
LB	static link
LB + 1	dynamic link
LB + 2	return address
LB + 3	z: *uninitialized*
LB + 4	x
LB + 5	x
ST	

Execution of the Example (4)

After `MUL`:

address	contents
...	...
SB + 42	n: n
...	...
LB − 2	x: x
LB − 1	y: y
LB	static link
LB + 1	dynamic link
LB + 2	return address
LB + 3	z: *uninitialized*
LB + 4	x^2
ST	

Execution of the Example (5)

After `LOAD [LB-1]; LOAD [LB-1]; MUL`:

address	contents
...	...
SB + 42	n: n
...	...
LB − 2	x: x
LB − 1	y: y
LB	static link
LB + 1	dynamic link
LB + 2	return address
LB + 3	z: *uninitialized*
LB + 4	x^2
LB + 5	y^2
ST	

Execution of the Example (6)

After `ADD`:

address	contents
...	...
SB + 42	n: n
...	...
LB − 2	x: x
LB − 1	y: y
LB	static link
LB + 1	dynamic link
LB + 2	return address
LB + 3	z: *uninitialized*
LB + 4	$x^2 + y^2$
ST	

Execution of the Example (7)

After `STORE [LB + 3]`:

address	contents
...	...
SB + 42	n: n
...	...
LB - 2	x: x
LB - 1	y: y
LB	static link
LB + 1	dynamic link
LB + 2	return address
LB + 3	z: $x^2 + y^2$
ST	

Execution of the Example (8)

After `LOAD [SB + 42]; LOAD [LB + 3]`:

address	contents
...	...
SB + 42	n: n
...	...
LB − 2	x: x
LB − 1	y: y
LB	static link
LB + 1	dynamic link
LB + 2	return address
LB + 3	z: $x^2 + y^2$
LB + 4	n
LB + 5	$x^2 + y^2$
ST	

Execution of the Example (9)

After `MUL`:

address	contents
...	...
SB + 42	n: n
...	...
LB − 2	x: x
LB − 1	y: y
LB	static link
LB + 1	dynamic link
LB + 2	return address
LB + 3	z: $x^2 + y^2$
LB + 4	$n(x^2 + y^2)$
ST	

Execution of the Example (10)

After `POP 1 1`:

address	contents
...	...
SB + 42	n: n
...	...
LB − 2	x: x
LB − 1	y: y
LB	static link
LB + 1	dynamic link
LB + 2	return address
LB + 3	$n(x^2 + y^2)$
ST	

`POP` is used here to tidy away the storage for local variables, preserving only the overall result.

Execution of the Example (11)

After `RETURN 1 2`:

address	contents
...	...
`SB + 42`	`n`: n
...	...
`Stack Top`	$n(x^2 + y^2)$
`ST`	

`RETURN` tidies away the rest of the activation record and returns to the caller.

`Stack Top` is in ***`f`'s caller's*** activation record, at some offset from `f`'s caller's LB.