Compiler Construction

Week 7: Code generation I

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2024/2025 KW3

Radboud University

Recap

Abstract machine

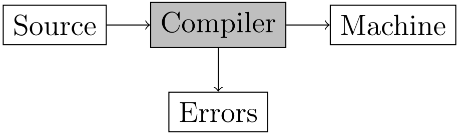
SSM

LLVM

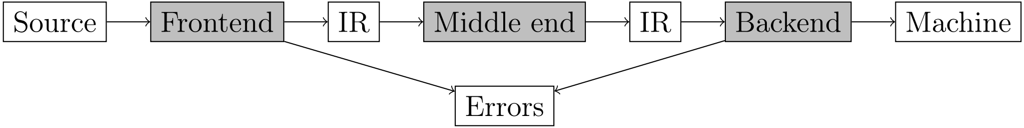
Conclusion

Recap

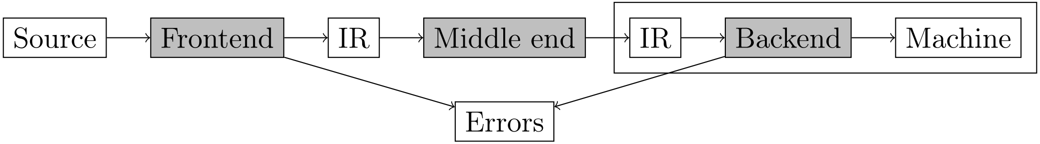
Compiler



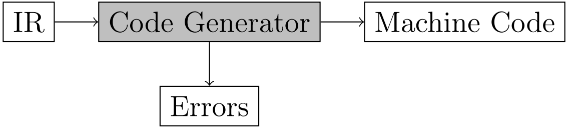
Three pass compiler



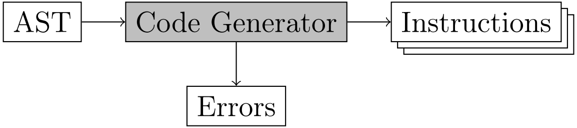
Three pass compiler



Backend

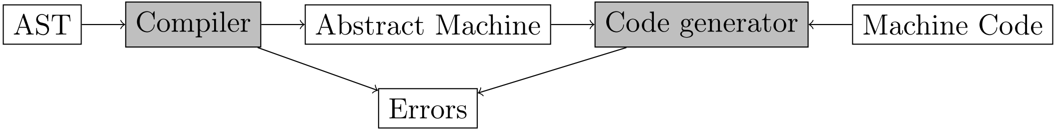


Backend



Abstract machine

Abstract machine



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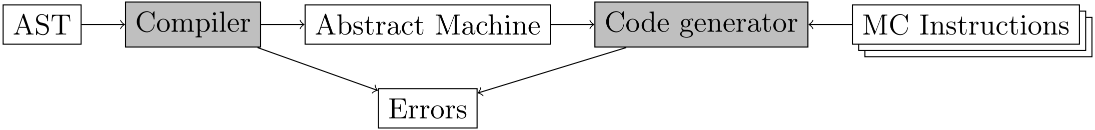

Abstract Machines

- Convenient middle ground

Abstract Machines

- Convenient middle ground
- Examples

Abstract Machines

- Convenient middle ground
- Examples
  - **LLVM**
  - ABC
  - **SSM**
  - C
  - C--

Abstract Machines

- Convenient middle ground
- Examples
- Similar Architecture but simplified

Abstract Machines

- Convenient middle ground
- Examples
- Similar Architecture but simplified
- Interpreter

Abstract Machines

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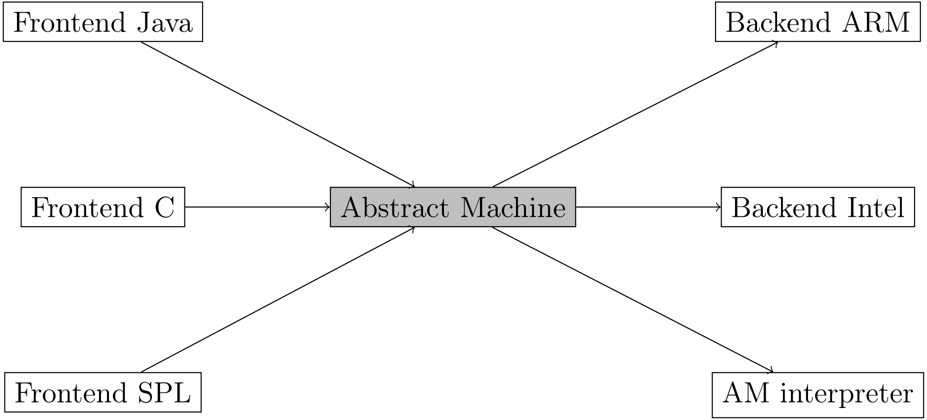
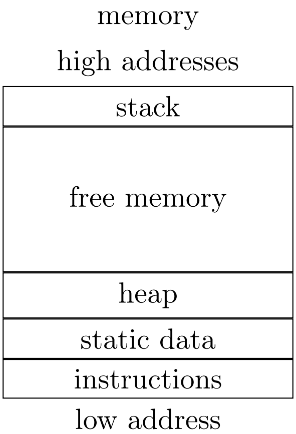


Abstract Machines

- Convenient middle ground
- Examples
- Similar Architecture but simplified
- Interpreter
- Assignment 3: Compiler SPL to SSM or LLVM*

Typical memory layout

Typical memory layout



memory

high addresses

stack

free memory

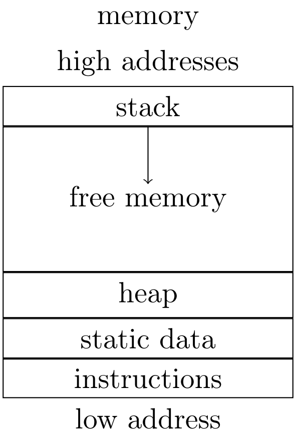
heap

static data

instructions

low address

Typical memory layout



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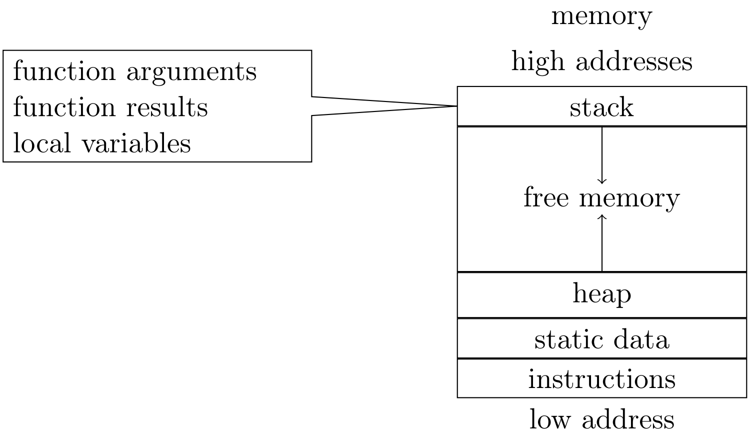


memory

high addresses

function arguments
function results
local variables

stack

free memory

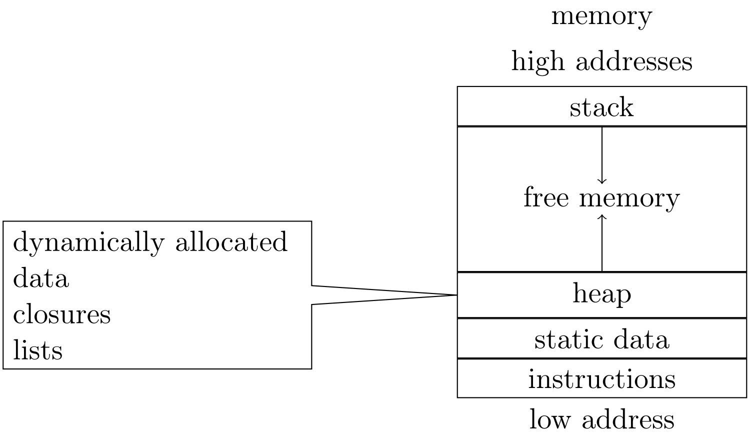
heap

static data

instructions

low address

Typical memory layout



memory

high addresses

stack

free memory

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instructions

low address

dynamically allocated data

closures

lists

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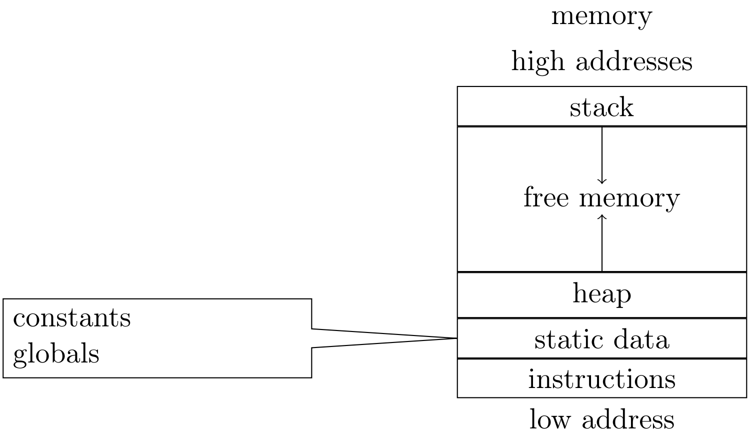

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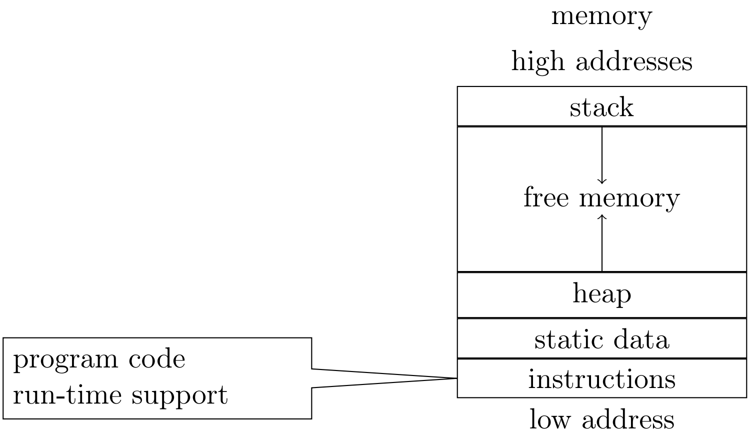

memory

high addresses

stack

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heap

static data

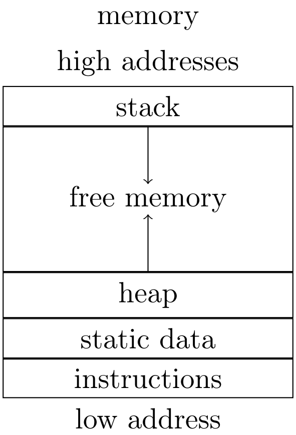
instructions

low address

program code

run-time support

Typical memory layout



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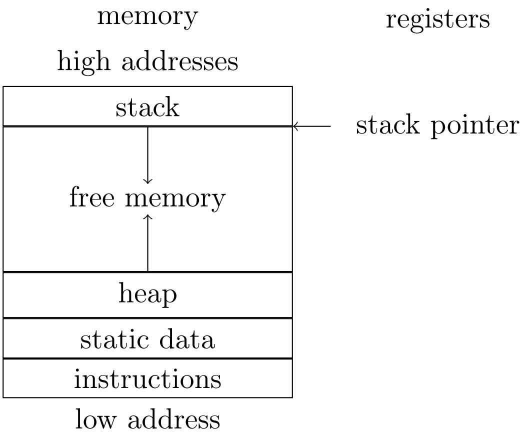

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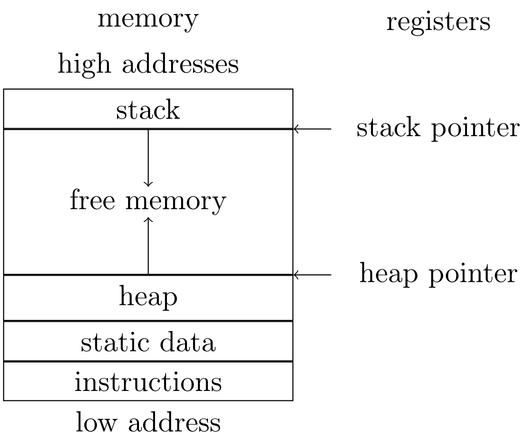

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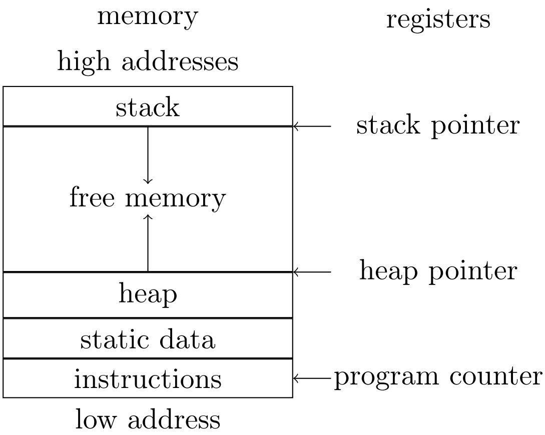

Typical memory layout

ABC memory layout

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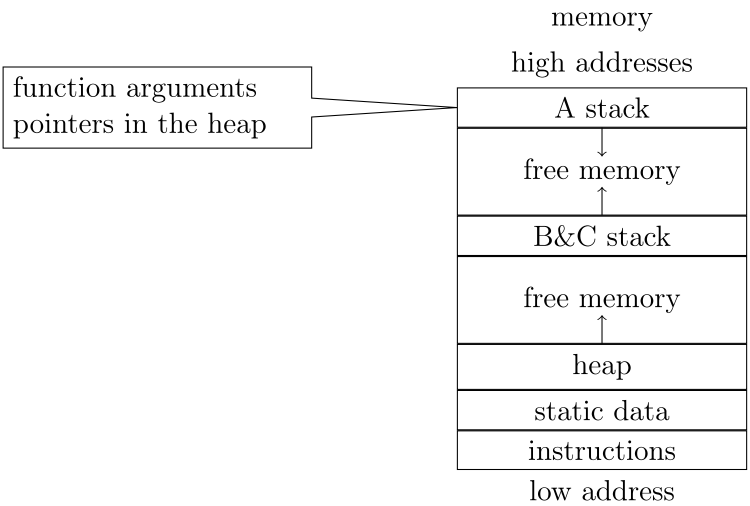

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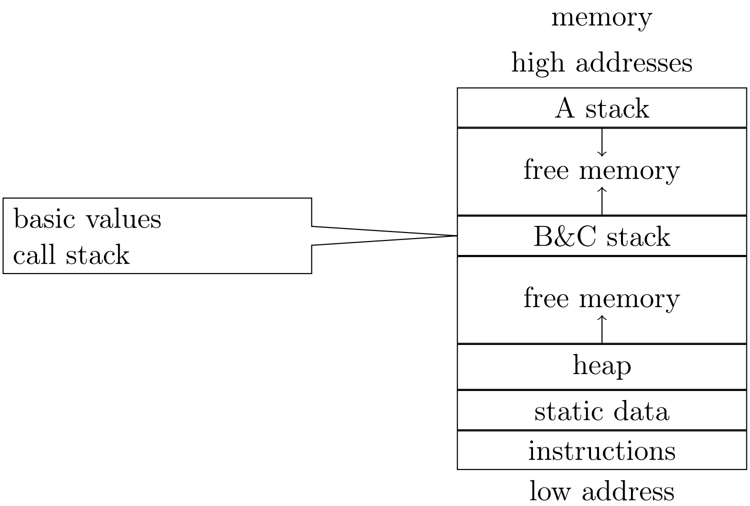
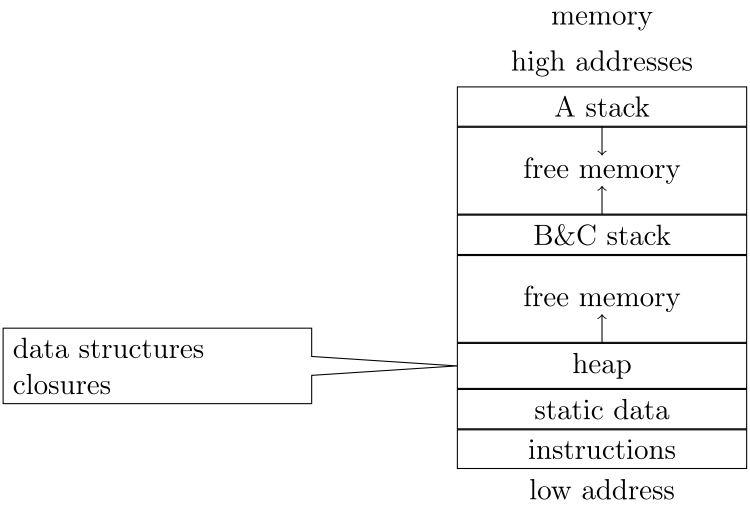


Typical memory layout

ABC memory layout



memory

high addresses

A stack

free memory

B&C stack

free memory

heap

static data

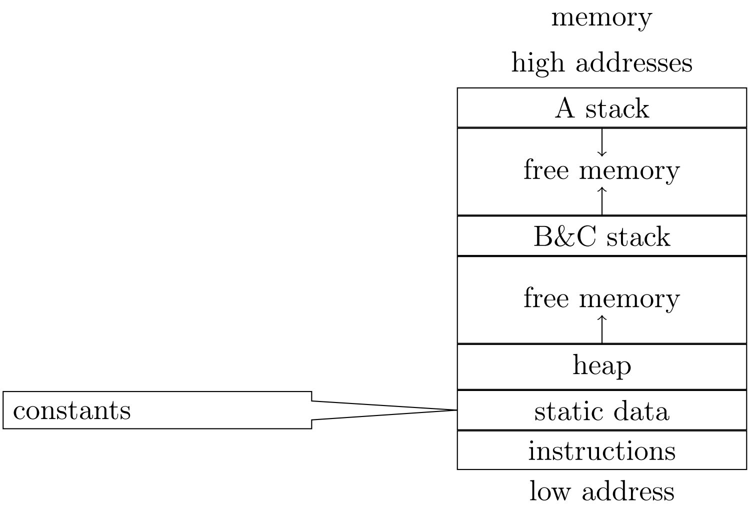
instructions

low address

data structures
closures

Typical memory layout

ABC memory layout



memory

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A stack

free memory

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heap

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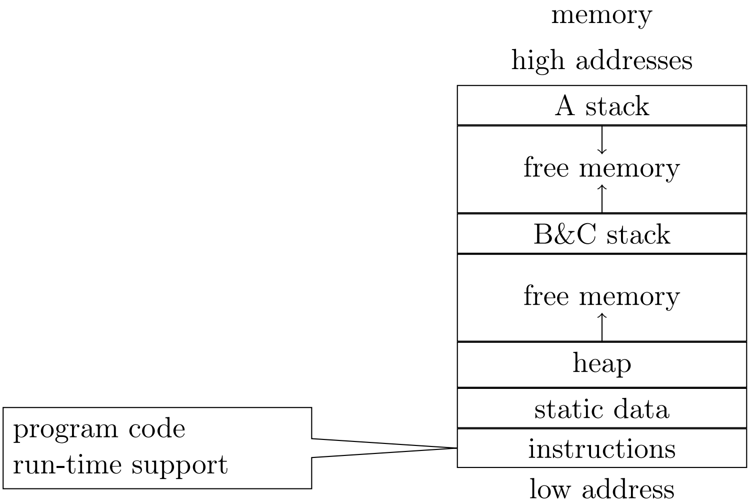
instructions

low address

constants

Typical memory layout

ABC memory layout



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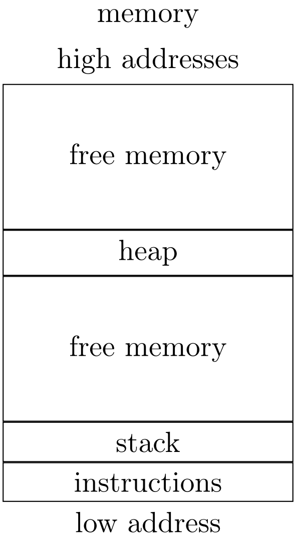
run-time support

Non-typical memory layout

Simple Stack Machine (SSM)



memory

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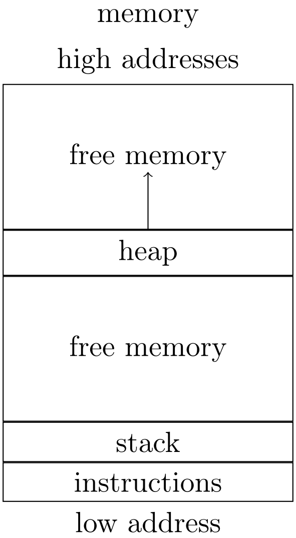

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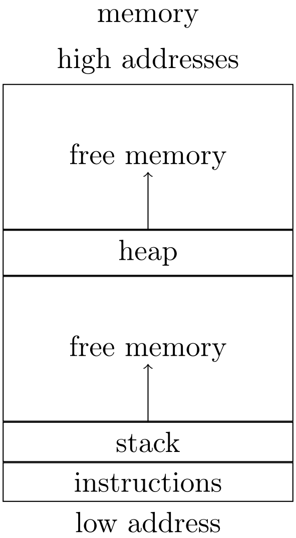

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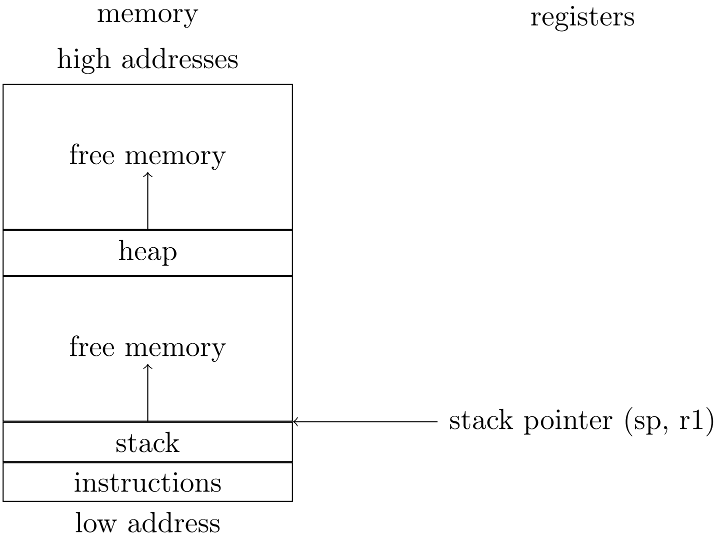

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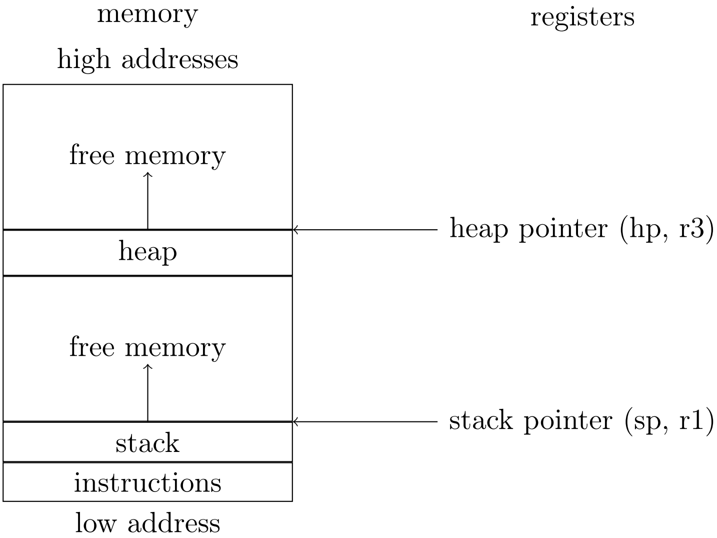

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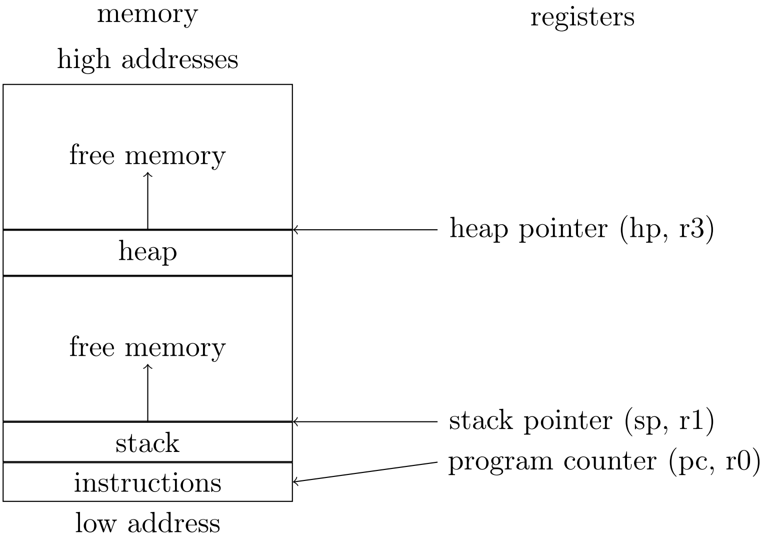

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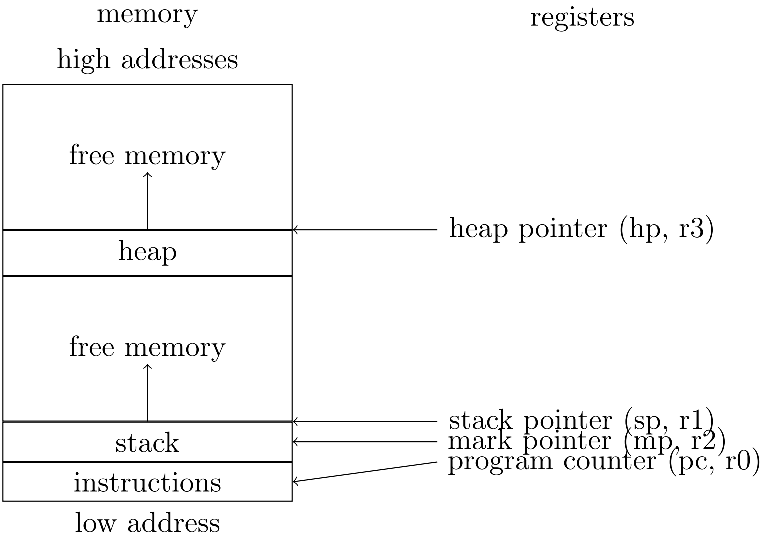

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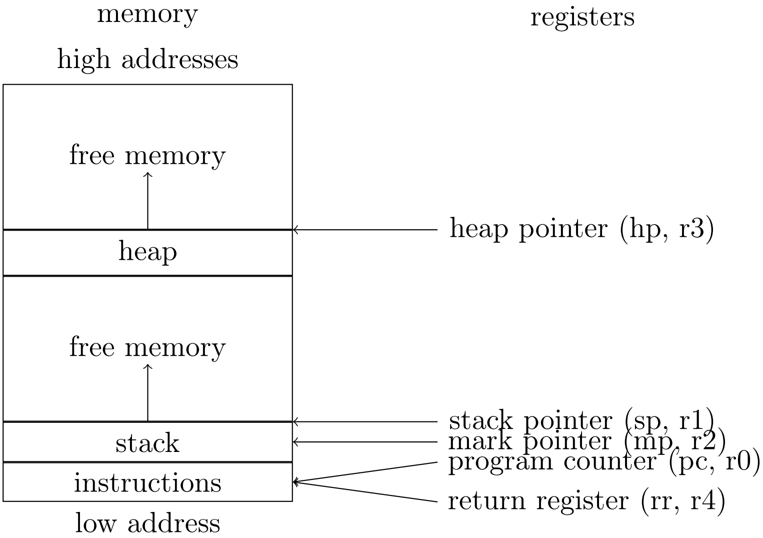

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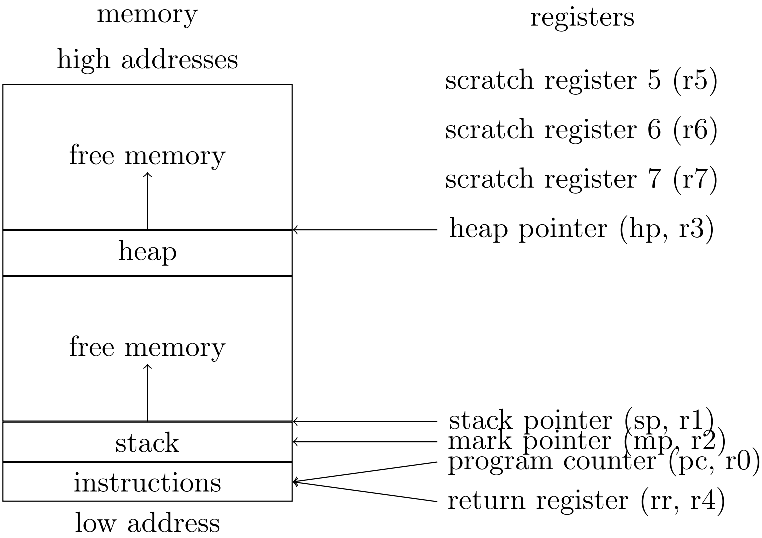


SSM

SSM Grammar

```
SSMProgram  ::= Line*
Line        ::= ((Label ":")?) (Instruction?) (Comment?)
Label       ::= Identifier
Instruction ::= ("ldc" | ...) Argument*
Argument    ::= Label | "-"? Number
Number      ::= Decimal | HexaDecimal
Decimal     ::= DecDigit*
HexaDecimal ::= "0x" HexDigit*
DecDigit    ::= "0" | .. |  "9"
HexDigit    ::= DecDigit | "a" | .. | "f" | "A" | .. | "F‘‘
Identifier  ::= DecDigit | "a" | .. | "z" | "A" | .. | "F" | "-" | "_"
Comment     ::= (";" | "//") .*
```

SSM Tip (1)

Annotate instructions

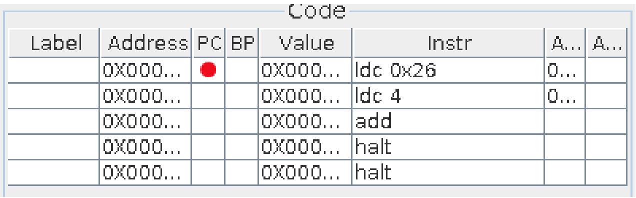
```
annote REG LOWOFFSET HIGHOFFSET COLOR MESSAGE
```

```
ldc 38
ldc 4
add
annote SP 0 0 red "The Answer"
halt
```

SSM Tip (1)

Annotate instructions

```
ldc 38
ldc 4
add
annote SP 0 0 red "The Answer"
halt
```



Code

Label	Address	PC	BP	Value	Instr	A...	A...
	0X000...	●		0X000...	ldc 0x26	0...	
	0X000...			0X000...	ldc 4	0...	
	0X000...			0X000...	add		
	0X000...			0X000...	halt		
	0X000...			0X000...	halt		

SSM Tip (1)

Annotate instructions

```
ldc 38
ldc 4
add
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```

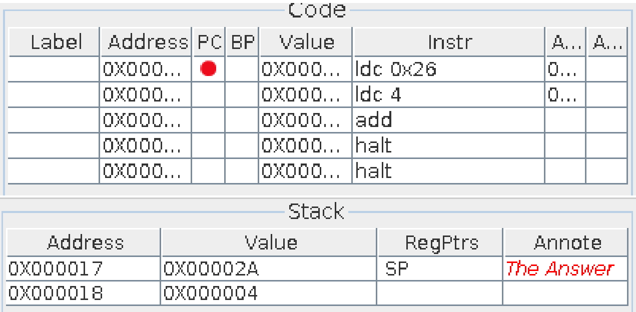

Code

Label	Address	PC	BP	Value	Instr	A...	A...
	0X000...	●		0X000...	ldc 0x26	0...	
	0X000...			0X000...	ldc 4	0...	
	0X000...			0X000...	add		
	0X000...			0X000...	halt		
	0X000...			0X000...	halt		

Stack

Address	Value	RegPtrs	Annote
0X000017	0X00002A	SP	*The Answer*
0X000018	0X000004		

SSM Tips (2)

CLI

```
frobnicator~/projects/ssm$ java -jar ssm.jar --help
Simple Stack Machine Interpreter
Version 2.4.0, May 10, 2022
usage: [--clisteps <steps>] [--cli] [--file <path> OR --stdin]
  --help               : Print this help
  --version            : Print version
  --clisteps <steps> : The amount of steps to run. -1 for infinite(default)
    .
                       Only in cli mode
  --stdin              : Read code from stdin
  --file <path>        : Read code from path
  --cli                : No GUI, runs code and exits on halt
  --haltonerror        : Halt on error. Only in cli mode
  --guidelay           : Amount of time to sleep in milliseconds between
    steps in
                       the GUI. Default: 50
```

SSM Tips (3)

Documentation

SSM Tips (3)

Documentation

Read the documentation

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SSM Tips (3)

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SSM Tips (3)

Documentation

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Instruction overview

<table>
<tr><th colspan="5">Copying</th></tr>
<tr><th>Load</th><th>Load Multiple</th><th>Load Address</th><th>Store</th><th>Store multiple</th></tr>
<tr><td>lda/ldh</td><td>ldma/ldmh</td><td>ldaa</td><td>sta</td><td>stma</td></tr>
<tr><td>lds</td><td>ldms</td><td>ldsa</td><td>sts</td><td>stms</td></tr>
<tr><td>ldl</td><td>ldml</td><td>ldml</td><td>stl</td><td>stml</td></tr>
<tr><td>ldc</td><td></td><td></td><td></td><td></td></tr>
<tr><th colspan="5">Register</th></tr>
<tr><td>ldr</td><td>str</td><td>str</td><td></td><td></td></tr>
<tr><td>swp</td><td>swpr</td><td>swprr</td><td></td><td></td></tr>
</table>

Instruction overview

Copying				
Load	Load Multiple	Load Address	Store	Store multiple
lda/ldh	ldma/ldmh	ldaa	sta	stma
lds	ldms	ldsa	sts	stms
ldl	ldml	ldml	stl	stml
ldc				
Register				
ldr	str	str		
swp	swpr	swprr		

ld	load	a/h	address	m	multiple
st	store	s	stack	-a	indirection
		l	local		
		c	constant		
		r	register		

Instruction overview

Copying				
Load	Load Multiple	Load Address	Store	Store multiple
lda/ldh	ldma/ldmh	ldaa	sta	stma
lds	ldms	ldsa	sts	stms
ldl	ldml	ldml	stl	stml
ldc				
Register				
ldr	str	str		
swp	swpr	swprr		

Documentation **lda**

```
SP_post = SP_pre
M_post[SP_post] = M_pre[M_pre[SP_pre] + M_pre[PC_pre+1]]
```

Instruction overview

Copying				
Load	Load Multiple	Load Address	Store	Store multiple
lda/ldh	ldma/ldmh	ldaa	sta	stma
lds	ldms	ldsa	sts	stms
ldl	ldml	ldml	stl	stml
ldc				
Register				
ldr	str	str		
swp	swpr	swprr		

Documentation **lds**

```
SP_post = SP_pre + 1
M_post[SP_post] = M_pre[SP_pre + M_pre[PC_pre+1]
```

Instruction overview

Copying				
Load	Load Multiple	Load Address	Store	Store multiple
lda/ldh	ldma/ldmh	ldaa	sta	stma
lds	ldms	ldsa	sts	stms
ldl	ldml	ldml	stl	stml
ldc				
Register				
ldr	str	str		
swp	swpr	swprr		

Documentation **ldl**

```
SP_post = SP_pre + 1
M_post[SP_post] = M_pre[MP_pre + M_pre[PC_pre+1]
```

Instruction overview

Copying				
Load	Load Multiple	Load Address	Store	Store multiple
lda/ldh	ldma/ldmh	ldaa	sta	stma
lds	ldms	ldsa	sts	stms
ldl	ldml	ldml	stl	stml
ldc				
Register				
ldr	str	str		
swp	swpr	swprr		

Documentation **ldc**

```
SP_post = SP_pre + 1
M_post[SP_post] = M_pre[PC_pre+1]
```

Instruction overview

Copying				
Load	Load Multiple	Load Address	Store	Store multiple
lda/ldh	ldma/ldmh	ldaa	sta	stma
lds	ldms	ldsa	sts	stms
ldl	ldml	ldml	stl	stml
ldc				
Register				
ldr	str	str		
swp	swpr	swprr		

Documentation **ldma**

```
displ = M_pre[PC_pre + 1]
size = M_pre[PC_pre + 2]
SP_post = SP_pre + size - 1
M_post[SP_post - size + 1 .. SP_post]
 = M_pre[M_pre[SP_pre] + displ .. M_pre[SP_pre] + displ + size - 1]
```

Instruction overview

		Copying		
Load	Load Multiple	Load Address	Store	Store multiple
lda/ldh	ldma/ldmh	ldaa	sta	stma
lds	ldms	ldsa	sts	stms
ldl	ldml	ldml	stl	stml
ldc				
		Register		
ldr	str	str		
swp	swpr	swprr		

Documentation **ldla**

```
SP_post = SP_pre + 1
M_post[SP_post] = MP_pre + M_pre[PC_pre+1]
```

Instruction overview

Arithmetics

Integer					
add	sub	mul	div	mod	neg
Comparison					
eq	ne	lt	le	gt	ge
Boolean					
and	or	xor	not		

Instruction overview

Arithmetics

Integer					
add	sub	mul	div	mod	neg
Comparison					
eq	ne	lt	le	gt	ge
Boolean					
and	or	xor	not		

Representation

- False: 0
- True: -1 (actually anything else)
- Integers: two's complement
- Characters: unicode integers

Instruction overview

Branching

<table>
<tr><th colspan="5">Adjust stack pointer</th></tr>
<tr><td>ajs</td><td></td><td></td><td></td><td></td></tr>
<tr><th colspan="5">Branch</th></tr>
<tr><td>bra</td><td>brt</td><td>brf</td><td></td><td></td></tr>
<tr><th colspan="5">Subroutines</th></tr>
<tr><td>bsr</td><td>jsr</td><td>ret</td><td>link</td><td>unlink</td></tr>
</table>

Subroutines

bsr	Branch to subroutine (push pc, jump)
jsr	Jump to subroutine (bsr but use pc from stack)
link	Allocate local variables (push mp, adjust sp)
unlink	Deallocate local variables (adjust sp, pop mp)
ret	Return from subroutine (pop pc, jump)

Instruction overview

Misc

nop
halt
trap

Instruction overview

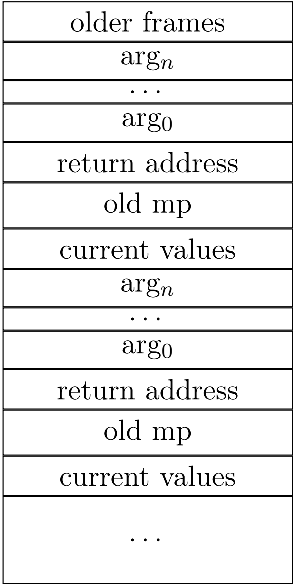
Misc

nop
halt
trap

No	Semantics
0	Print int
1	Print char
2	Print char array
10	Ask integer
11	Ask char
12	Ask char array
20	open file for reading
21	open file for writing
22	read char from file
23	write char to file
24	close file

Stack Frames

- Where to store things



older frames

arg_n

$\ldots$

arg_0

return address

old mp

current values

arg_n

$\ldots$

arg_0

return address

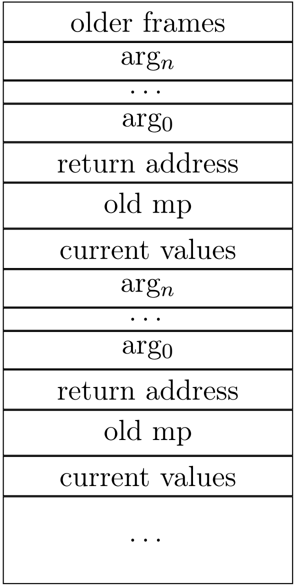
old mp

current values

$\ldots$

Stack Frames

- Where to store things
- Arguments



older frames

arg_n

…

arg_0

return address

old mp

current values

arg_n

…

arg_0

return address

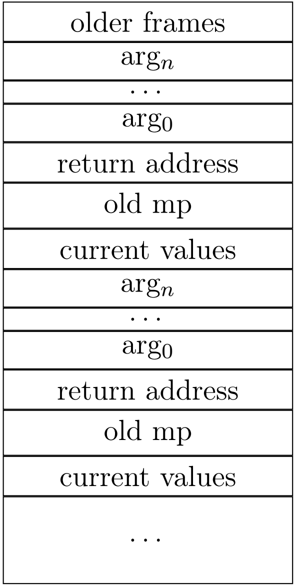
old mp

current values

…

Stack Frames

- Where to store things
- Arguments
- Locals



older frames

arg_n

$\ldots$

arg_0

return address

old mp

current values

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Stack Frames

- Where to store things
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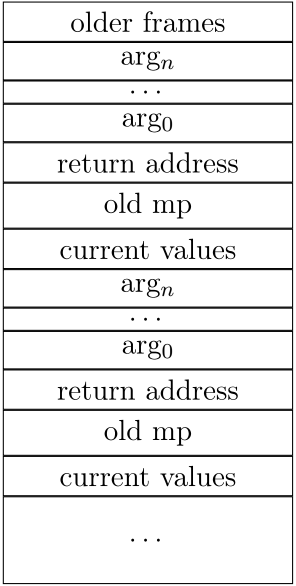
- Locals
- Globals (later)



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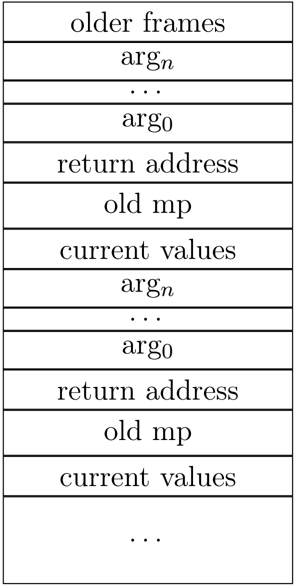

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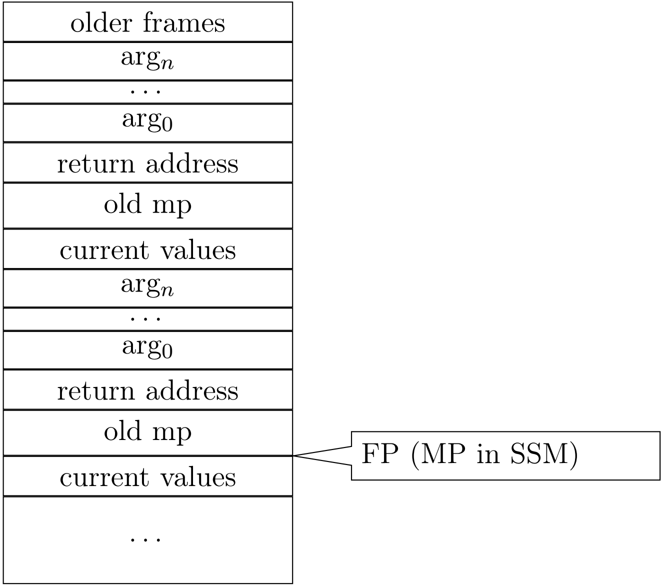

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FP (MP in SSM)

Stack Frames

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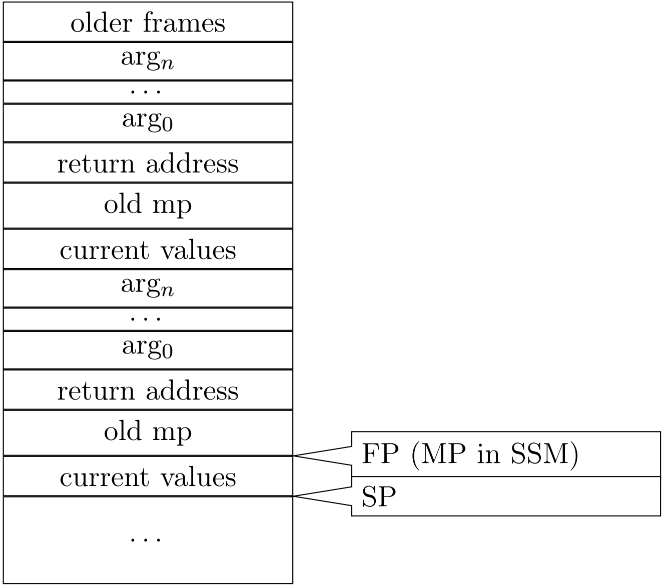
- Arguments
- Locals
- Globals (later)



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FP (MP in SSM)

SP

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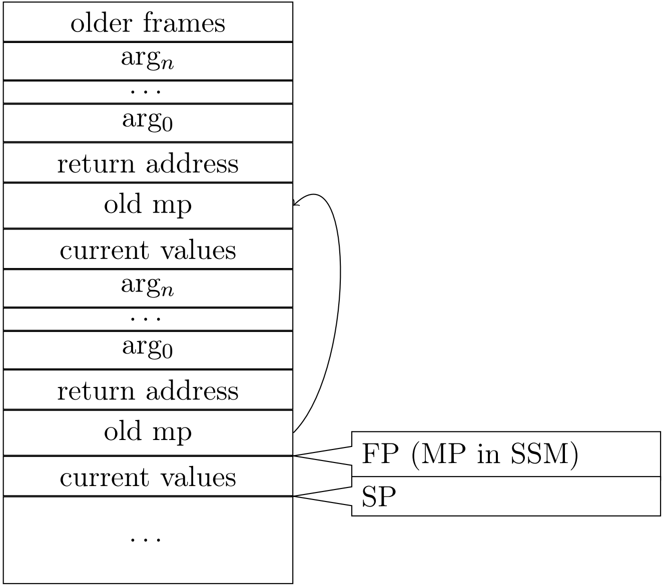

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old mp

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FP (MP in SSM)

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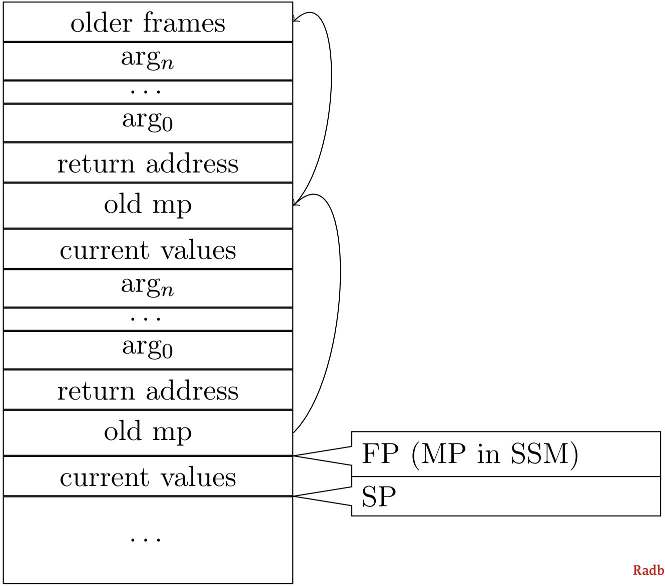

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FP (MP in SSM)

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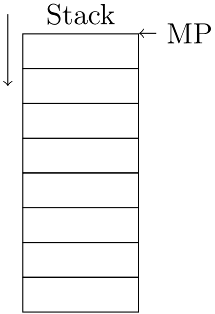

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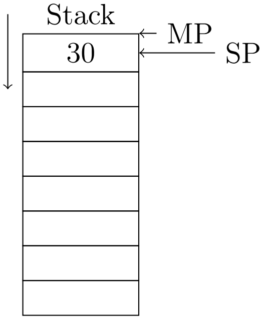

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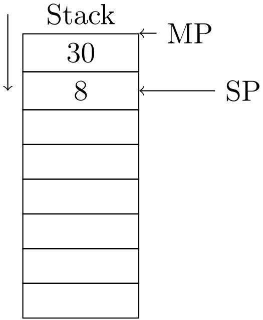

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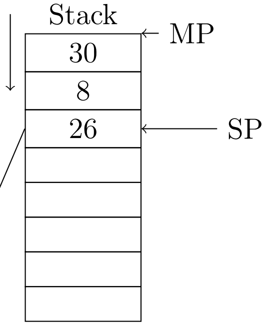

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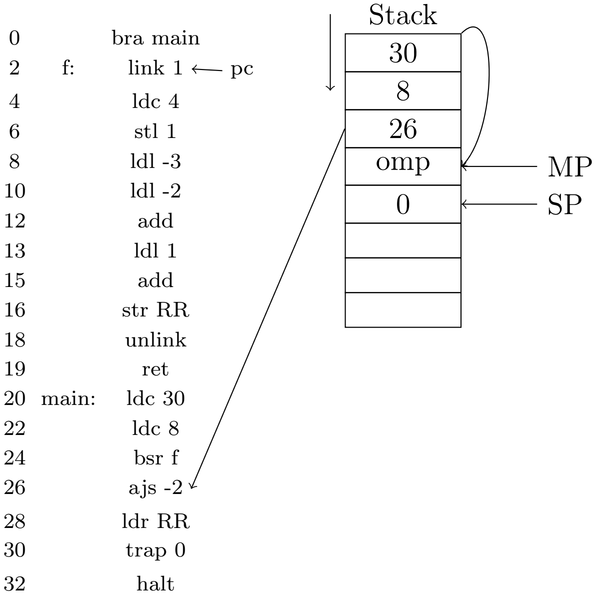

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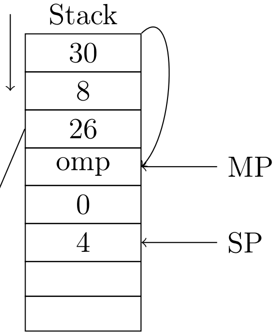

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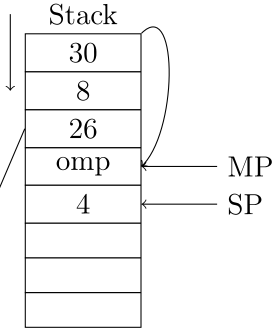

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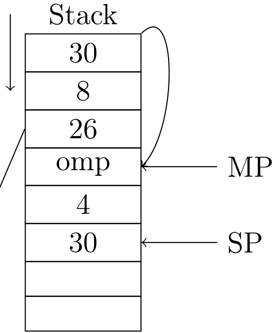

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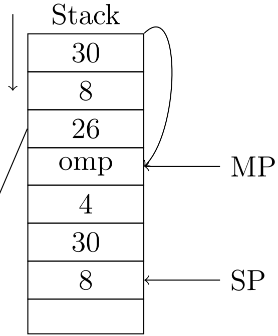

Stack

30

8

26

omp ← MP

4

30

8 ← SP

Stack Frame Example

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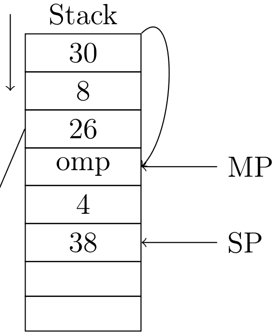

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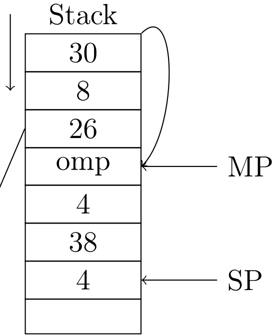

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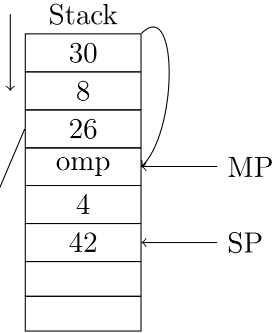

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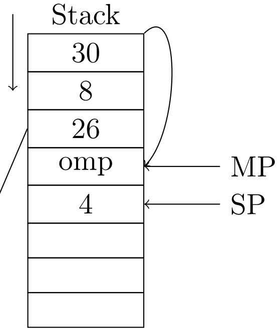

Stack

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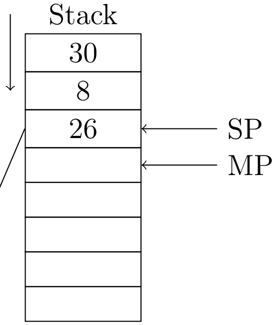

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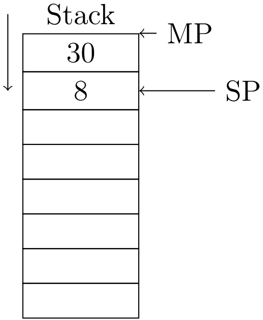

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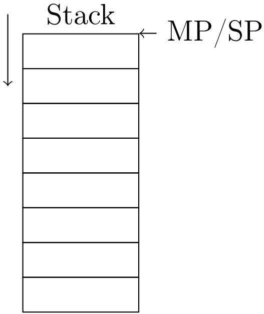

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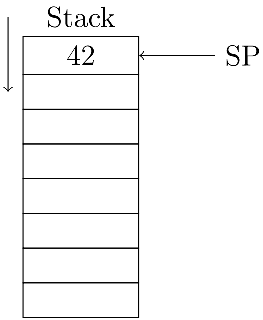

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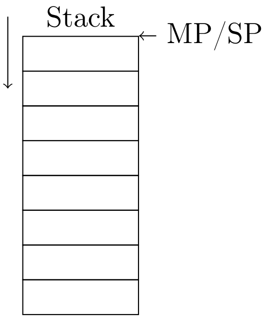

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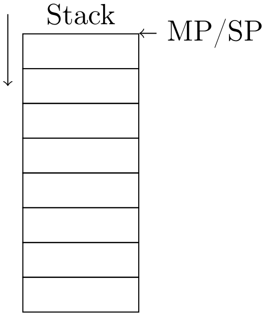

SSM Tips (4)

Globals

- When to calculate

SSM Tips (4)

Globals

- When to calculate
- How to retrieve

SSM Tips (4)

Globals

- When to calculate
- How to retrieve
- Addresses in spare register

LLVM

LLVM

LLVM

- Optimiser and code generator

LLVM

- Optimiser and code generator and JIT compiler, dynamic linker, debugger, …
- Low level virtual machine

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How to use LLVM-IR

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Bitcode

- Binary encoding
- Fast parsing
- More difficult to output
- Not stable*

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C++ classes

- Direct in-memory encoding of the IR
- Requires an FFI to the C++ library
- Fairly convoluted
- But stable

Example

Hello World!

Example

Hello World!

```
; Define the target
target triple = "x86_64-pc-linux-gnu"

; Declare the string constant as a global constant.
@.str = private unnamed_addr constant [14 x i8] c"Hello World!\0A\00"

; External declaration of the puts function
declare i32 @puts(ptr) nounwind

; Definition of main function
define i32 @main() {
  ; Call puts function to write out the string to stdout.
  call i32 @puts(ptr @.str)
  ret i32 0
}
```

Example

Hello World!

```
; Definition of main function
define i32 @main() {
  ; Call puts function to write out the string to stdout.
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```

How to run (on Linux at least)

```
$ clang hello.ll -o hello
$ ./hello
Hello World!
```

Example

Use printf

Example

Use printf

```
; Declare the string constant as a global constant.
@.str = private unnamed_addr constant [4 x i8] c"%d\0A\00"

; External declaration of the puts function
declare i32 @printf(ptr, ...) nounwind

; Definition of main function
define i32 @main() {
  %1 = add i32 38, 4
  %2 = add i32 %1, %1
  call i32 @printf(ptr @.str, i32 %2)
  ret i32 0
}
```

Example

Use printf

```
; External declaration of the puts function
declare i32 @printf(ptr, ...) nounwind

; Definition of main function
define i32 @main() {
  %1 = add i32 38, 4
  %2 = add i32 %1, %1
  call i32 @printf(ptr @.str, i32 %2)
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Use printf

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; External declaration of the puts function
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define i32 @main() {
  %1 = add i32 38, 4
  %2 = add i32 %1, %1
  call i32 @printf(ptr @.str, i32 %2)
  ret i32 0
}
```

Output

```
$ clang hello2.ll -o hello2
$ ./hello2
42
```

Example

Static Single assignment

Example

Static Single assignment

```
; Definition of main function
define i32 @main() {
  %1 = add i32 38, 4
  %2 = add i32 %1, %1
  %2 = add i32 %1, 84
  call i32 @printf(ptr @.str, i32 %2)
  ret i32 0
}
```

Example

Static Single assignment

```
; Definition of main function
define i32 @main() {
  %1 = add i32 38, 4
  %2 = add i32 %1, %1
  %2 = add i32 %1, 84
  call i32 @printf(ptr @.str, i32 %2)
  ret i32 0
}
```

Output

```
$ clang ssa.ll -o ssa
ssa.ll:15:2: error: instruction expected to be numbered '%3' or greater
   15 |        %2 = add i32 %1, 84
      |        ^
1 error generated.
```

Static Single assignment

Pragmatic overview

- You can assign a register only once
- i.e. pick a fresh one for each intermediate value
- So `f (x) { return x + (1 + 2) * (3 - 4);}` translates to:

```
define i32 @f(i32 %x) {
  %1 = add i32 1, 2
  %2 = sub i32 3, 4
  %3 = mul i32 %1, %2
  %4 = add i32 %x, %3
  ret i32 %4
}
```

Mapping high-level constructs on LLVM-IR

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  Maps all needed constructs, e.g.
- Local variables
  use **alloca** to allocate on the stack
- If statements
  use labels (`lbl:`) and branching (**br**) but be aware of SSA!
- Etcetera...

Conclusion

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Assignment

- Start implementing your code generator

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  - Reference and interpreter:
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- Think about an extension
- Deadline: day after next lecture.