Run-Time Environments

Where we are:

- We have covered the front-end phases
  - Lexical analysis
  - Parsing
  - Semantic analysis
- The front-end phases enforce the definition of the language (syntax)
- It also builds data structures for code generation
- The output of the front end are legal programs
- Next are the back-end phases
  - Optimization
  - Code generation
- We'll do code generation first . . .

- In the back-end phases we are **no longer looking for errors.**
- We are **ready to perform code generation**
- Before discussing code generation**, we need to understand what we are trying to generate**
- There are a number of standard techniques for **structuring executable code** that are widely used

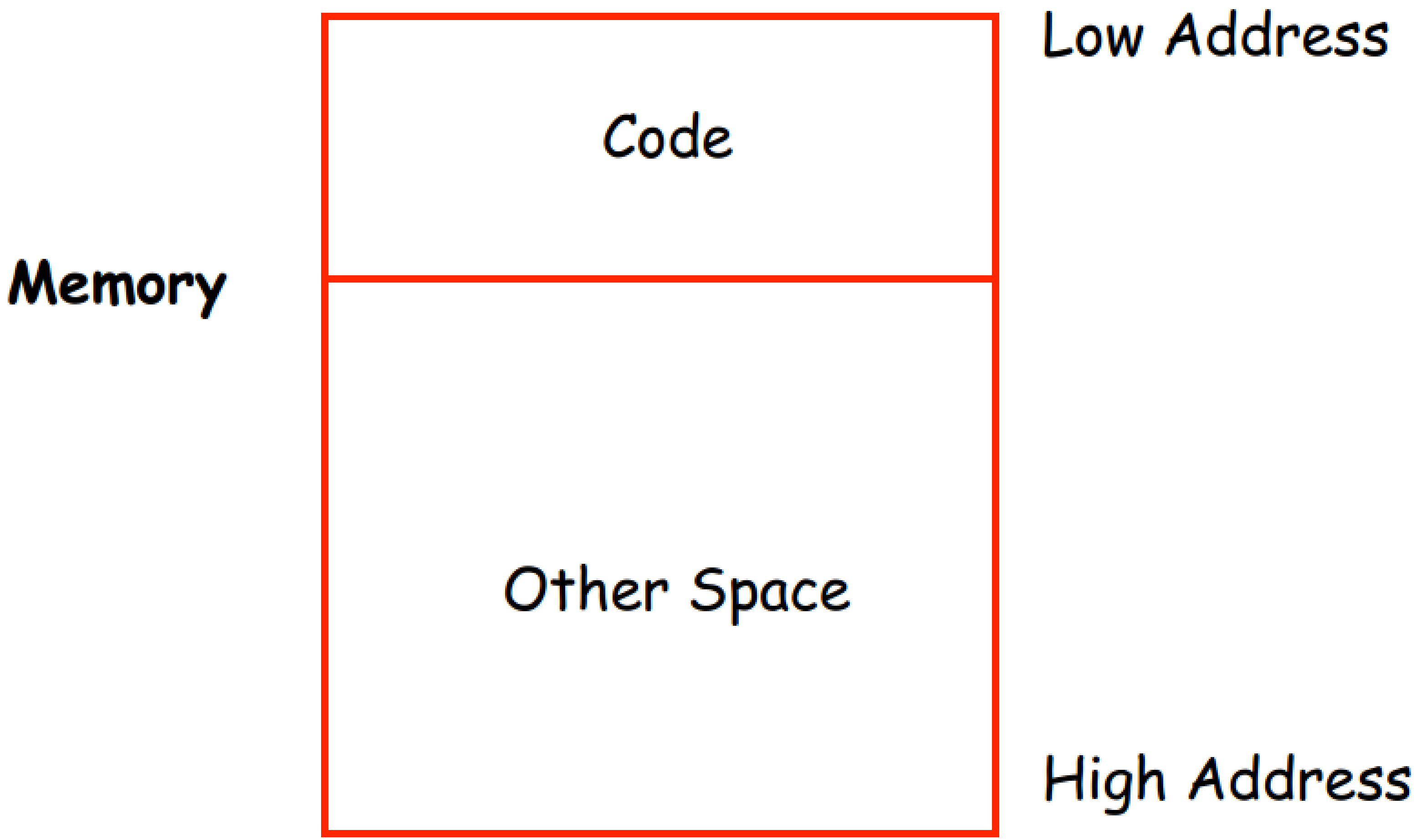
Outline

- Management of run-time resources
- Correspondence between
  - static (compile-time) and
  - dynamic (run-time) structures
- Storage organization

Run-time Resources

- Execution of a program is initially under the control of the operating system
- When a program is invoked:
  - The OS allocates space for the program
  - The code is loaded into part of the space
  - The OS jumps to the entry point (i.e., “main”)

Memory Layout



Notes

- By tradition, pictures of machine organization have:
  - Low address at the top
  - High address at the bottom
  - Lines delimiting areas for different kinds of data
- These pictures are simplifications
  - E.g., not all memory need be contiguous

What is Other Space?

- Holds all data for the program
- Other Space = Data Space
- Compiler is responsible for:
  - Generating code
  - Orchestrating use of the data area

Code Generation Goals

- Two goals:
  - Correctness
  - Speed
- Most complications in code generation come from trying to be fast as well as correct

Assumptions about Execution

1. Execution is sequential; control moves from one point in a program to another in a well-defined order
2. When a procedure is called, control eventually returns to the point immediately after the call

Activations

- An invocation of procedure P is an activation of P
- The life time of an activation of P is
  - All the steps to execute P
  - Including all the steps in procedures P calls

Lifetimes of Variables

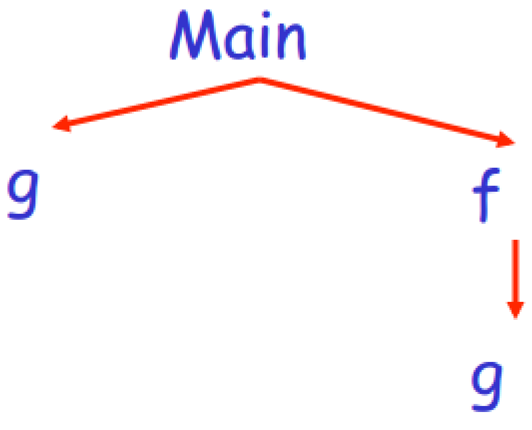
- The lifetime of a variable x is the portion of execution in which x is defined
- Note that
  - Lifetime is a dynamic (run-time) concept
  - Scope is a static concept

Activation Trees

- Assumption (2) requires that when P calls Q, then Q returns before P does
- Lifetimes of procedure activations are properly nested
- Activation lifetimes can be depicted as a tree

Example

```
Class Main {
   g() : Int { 1 };
   f():  Int { g() };
   main(): Int {{ g(); f(); }};
}
```



A More Complex example: recursive

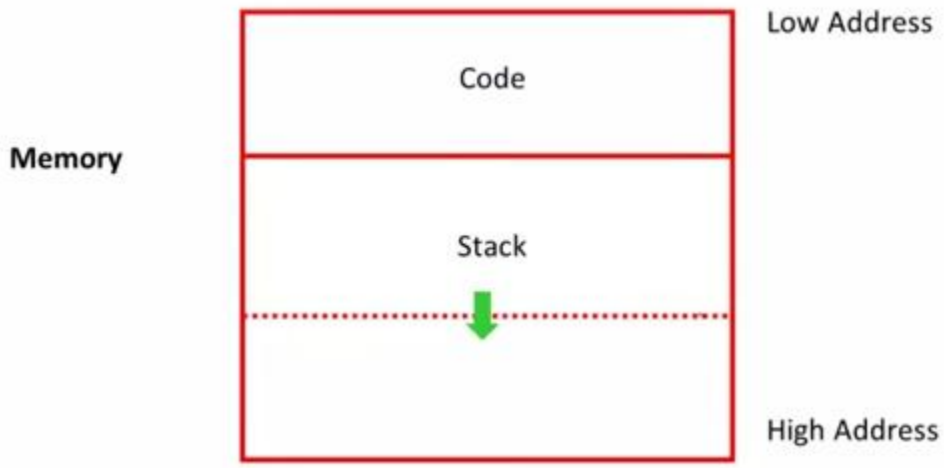
```
 class Main{
    int g(){ ….}
    int f( int x){
                     if(x==0) then return g();
                      else return f(x-1);
     }
int main() { return f(3);}
```

What is the activation tree for this program?

Notes

- The activation tree depends on run-time behavior
- The activation tree may be different for every program input
- Since activations are properly nested, a stack can track currently active procedures

Revised Memory Layout



Activation Records

- The information needed to manage one procedure activation is called an activation record (AR) or frame.

- If procedure F calls G, then G's activation record contains a mix of info about F and G.

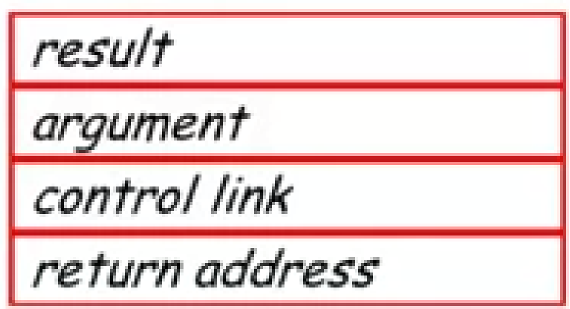
What is in G’s AR when F calls G?

- F is “suspended” until G completes, at which point F resumes.
- G’s AR contains information needed to resume execution of F.
- G’s AR may also contain:
  - G’s return value (needed by F)
  - Actual parameters to G(supplied by F)
  - Space for G’s local variables

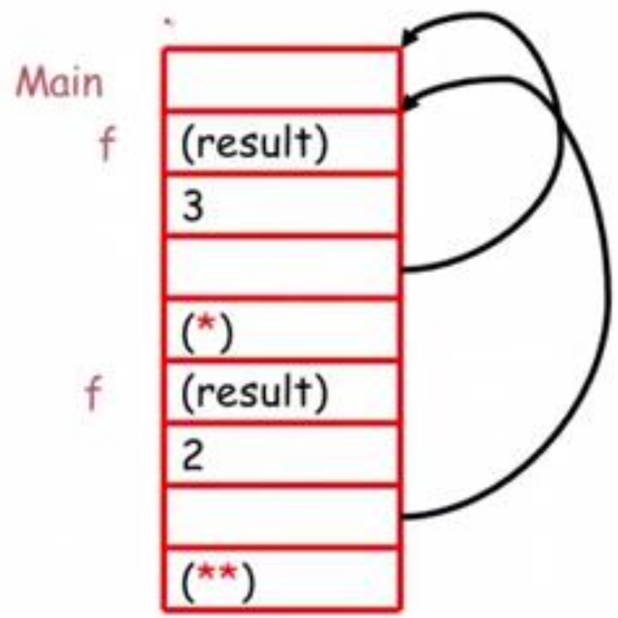
The Contents of a Typical AR for G

- Space for G’s return value
- Actual parameters
- Pointer to the previous activation record
  - The control link; points to AR of caller of G
- Machine status prior to calling G
  - Contents of registers & program counter
  - Local variables
- Other temporary values

```
class Main{
     int g(){ ….}
     int f( int x){
                          if(x==0) then return g();
                           else return f(x-1)  (**);
      }
int main() { return f(3)  (*);}
```



Stack after two calls to f



Notes

- Main has no argument or local variables and its result is never used; its AR is uninteresting
- (*) and (**) are return addresses of the invocations of f
- The return address is where execution resumes after a procedure call finishes
- This is only one of many possible AR designs
  - Would also work for C, Pascal, FORTRAN, etc.

The Main Point

- The compiler must determine, at compile-time, the layout of activation records and generate code that correctly accesses locations in the activation record
- Thus, the AR layout and the code generator must be designed together!

Discussion

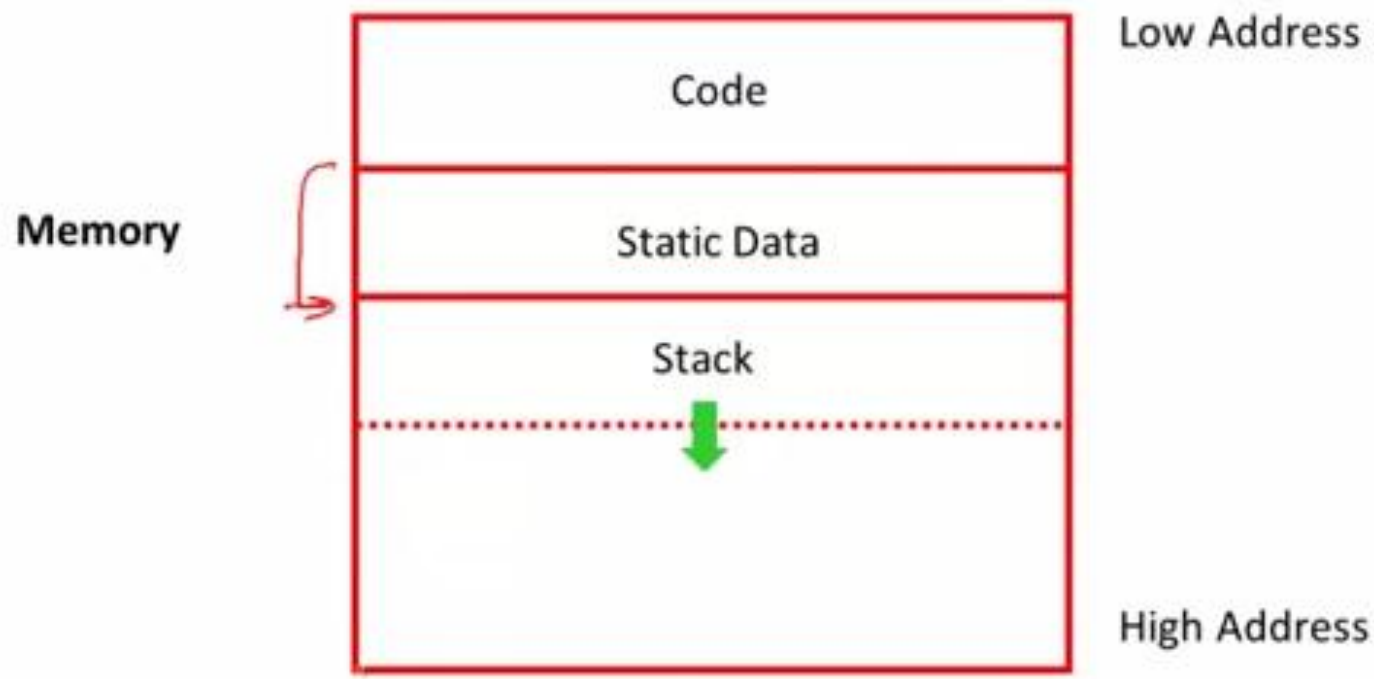
- The advantage of **placing the return value 1st in a frame** is that the caller can find it at a fixed offset from its own frame
- There is **nothing magic** about this organization
  - Can rearrange order of frame elements
  - Can divide caller/callee responsibilities differently
  - An organization is better if it **improves execution speed or simplifies code generation**

- Real compilers hold as much of the frame as possible in registers
  - Especially the method result and arguments

Global Variables

- All references to a global variable point to the same object
  - Can't store a global in an activation record
- Globals are assigned a fixed address once
  - Variables with fixed address are "statically allocated"
- Depending on the language, there may be other statically allocated values

Memory Layout with Static Data



Heap Storage

- A value that outlives the procedure that creates it cannot be kept in the AR

  method foo() { new Bar }

- The Bar value must survive deallocation of foo's AR
- Languages with dynamically allocated data use a heap to store dynamic data

Notes

- The code area contains object code
  - For most languages, fixed size and read only
- The static area contains data (not code) with fixed addresses (e.g., global data)
  - Fixed size, may be readable or writable
- The stack contains an AR for each currently active procedure
  - Each AR usually fixed size, contains locals
- Heap contains all other data
  - In C, heap is managed by malloc and free

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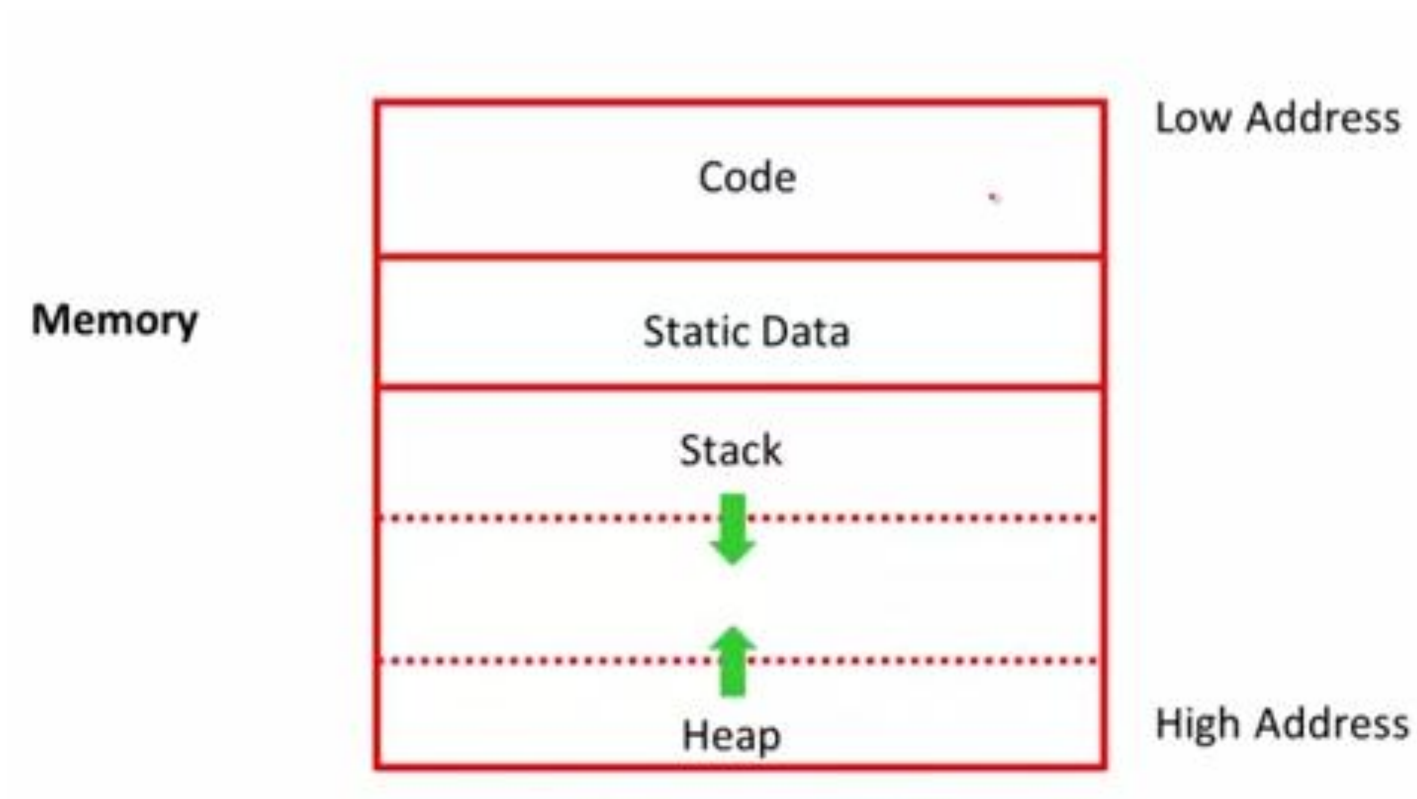
Notes (Cont.)

- Both the heap and the stack grow
- Must take care that they don't grow into each other
- Solution: start heap and stack at opposite ends of memory and let them grow towards each other

Memory Layout with Heap



Data Layout

- Low-level details of machine architecture are important in laying out data for correct code and maximum performance
- Chief among these concerns is alignment

Alignment

- Most modern machines are (still) 32 bit
  - 8 bits in a byte
  - 4 bytes in a word
  - Machines are either byte or word addressable
- Data is word alignedif it begins at a word boundary
- Most machines have some alignment restrictions
  - Or performance penalties for poor alignment

Alignment

- Example: A string

“Hello”

Takes 5 characters (without a terminating \0)

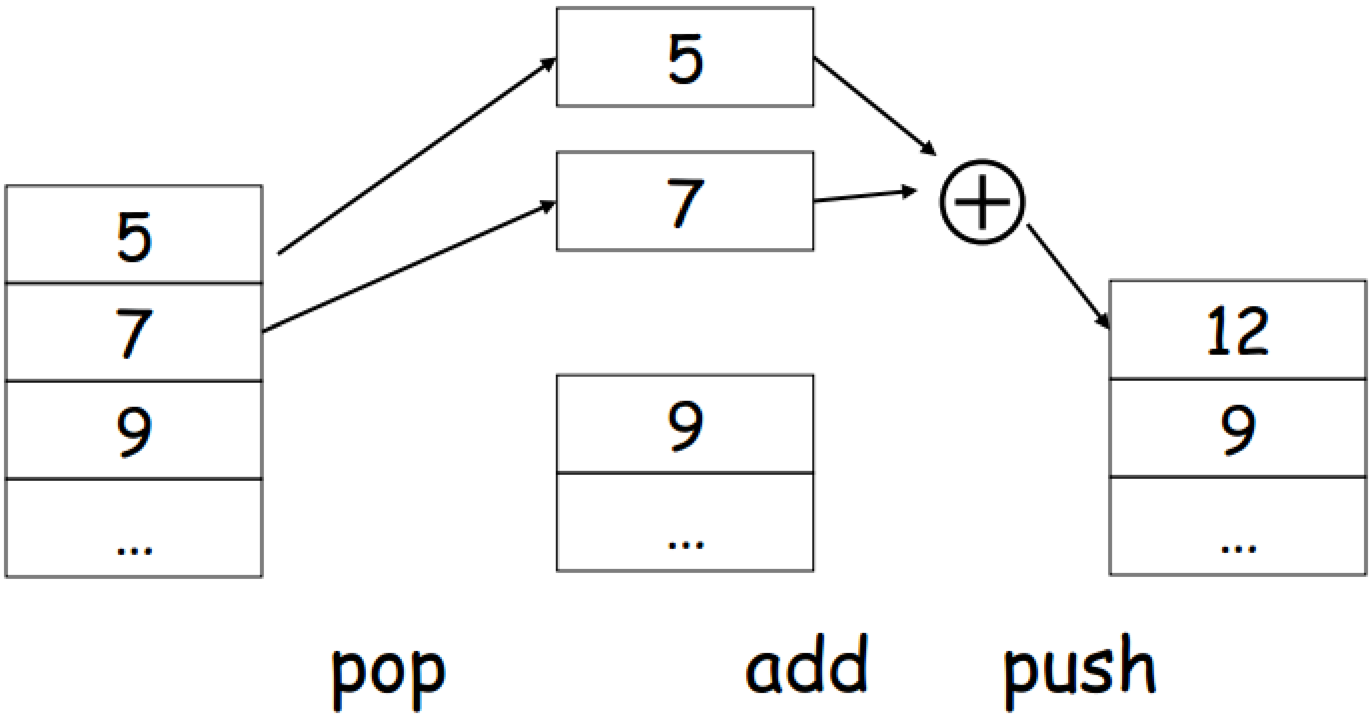
- To word align next datum, add 3 “padding” characters to the string
- The padding is not part of the string, it’s just unused memory

Next Topic: Stack Machines

- A simple evaluation model
- No variables or registers
- A stack of values for intermediate results
- Each instruction:
  - Takes its operands from the top of the stack
  - Removes those operands from the stack
  - Computes the required operation on them
  - Pushes the result on the stack

Example of Stack Machine Operation

- The addition operation on a stack machine



Example of a Stack Machine Program

- Consider two instructions
  - push i- place the integer ion top of the stack
  - add- pop two elements, add them and put the result back on the stack
- A program to compute 7 + 5:

```
push 7
push 5
add
```

Why Use a Stack Machine ?

- Each operation takes operands from the same place and puts results in the same place
- This means a uniform compilation scheme
- And therefore a simpler compiler

Why Use a Stack Machine ?

- Location of the operands is implicit
  - Always on the top of the stack
- No need to specify operands explicitly
- No need to specify the location of the result
- Instruction "add" as opposed to "add r1, r2"
  - ⇒Smaller encoding of instructions
  - ⇒More compact programs
- This is one reason why Java Bytecodes use a stack evaluation model

Optimizing the Stack Machine

- The add instruction does 3 memory operations
  - Two reads and one write to the stack
  - The top of the stack is frequently accessed
- Idea: keep the top of the stack in a register (called accumulator)
  - Register accesses are faster
- The "add" instruction is now

$$acc \leftarrow acc + top\_of\_stack$$

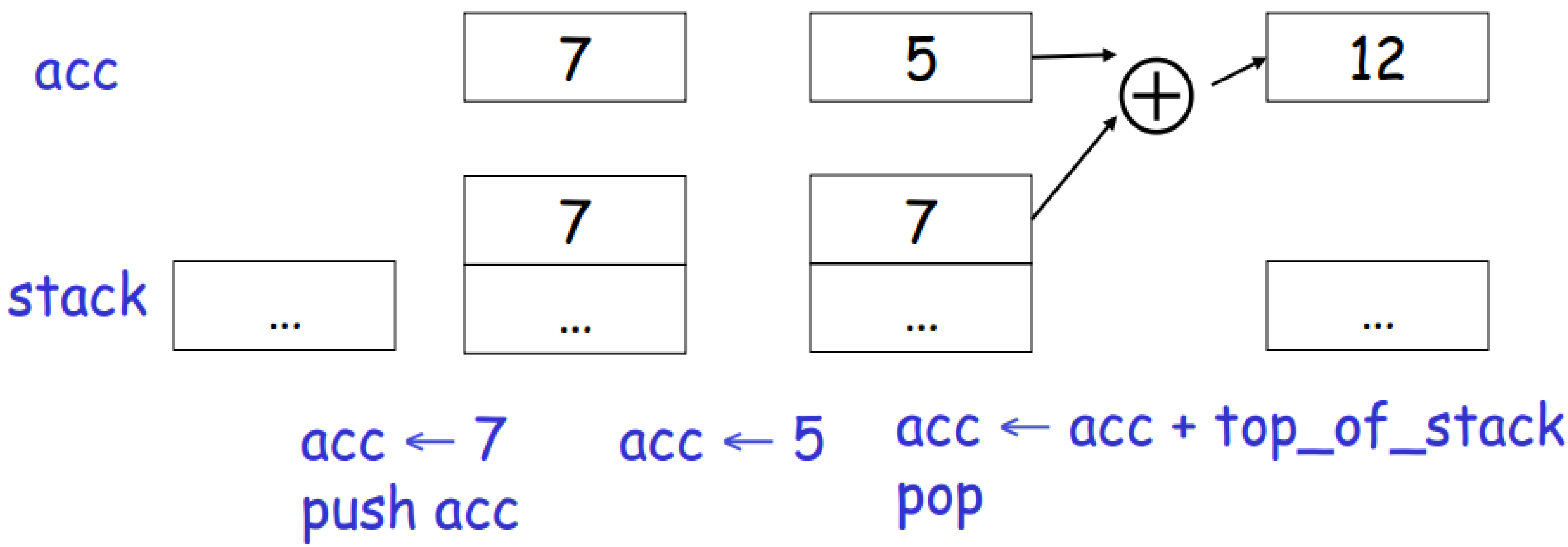
  - Only one memory operation!

Stack Machine with Accumulator

- Invariants
  - The result of an expression is in the accumulator
- For op(e1,…,en) push the accumulator on the stack after computing e_1,…,e_{n-1}
  - After the operation pops n-1 values
- Expression evaluation preserves the stack

Stack Machine with Accumulator. Example

- Compute 7 + 5 using an accumulator



A Bigger Example: 3 + (7 + 5)

Code	**Acc**	**Stack**
acc ←3	3	<init>
push acc	3	3, <init>
acc ←7	7	3, <init>
push acc	7	7, 3, <init>
acc ←5	5	7, 3, <init>
acc ←acc + top_of_stack	12	7, 3, <init>
pop	12	3, <init>
acc ←acc + top_of_stack	15	3, <init>
pop	15	<init>

Notes

- It is very important evaluation of a subexpression preserves the stack
  - Stack before the evaluation of 7 + 5 is 3, <init>
  - Stack after the evaluation of 7 + 5 is 3, <init>
  - The first operand is on top of the stack