RUN-TIME ENVIRONMENTS

Baishakhi Ray

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- We have covered the front-end phases
  - Lexical analysis
  - Parsing
  - Semantic analysis

All the compilation errors are caught in this phase

- Next are the back-end phases
  - Code generation
  - Optimization

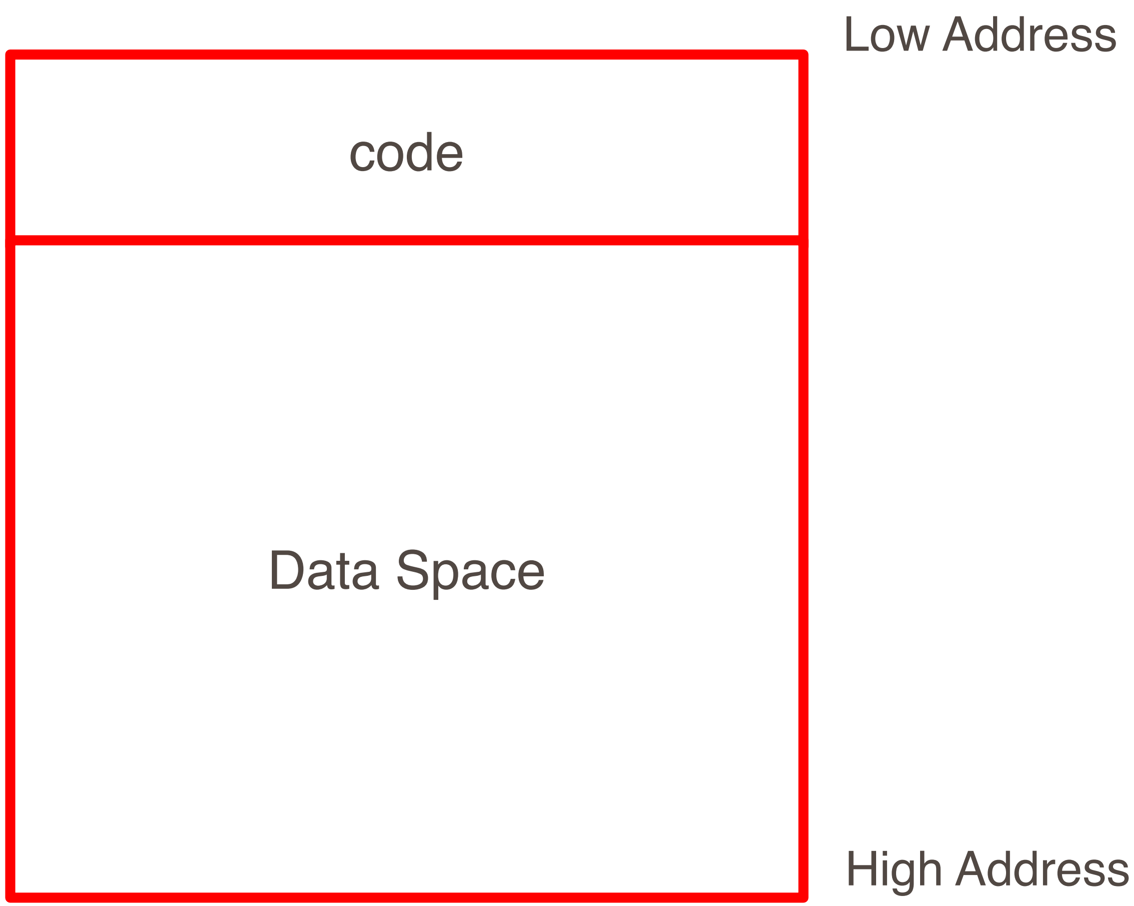
Run-time environments

- What are we trying to generate?
- How executable code is laid out?

Run-time Processes

- 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



- By tradition
  - Low address at the top
  - High address at the bottom
  - Lines delimiting areas for different kinds of data
- Simplified representation
  - Not all memory need be contiguous
- 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

- Execution is sequential
  - control moves from one point in a program to another in a well-defined order
- 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 lifetime of an activation of P is
  - All the steps to execute P
  - Including all the steps in procedures P calls

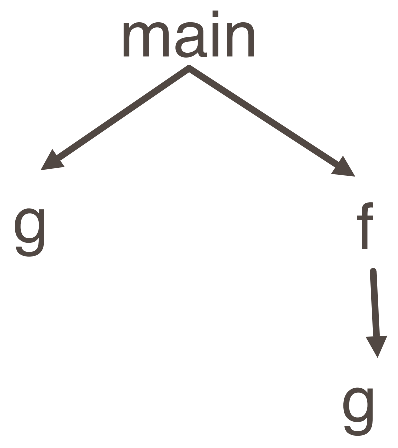
- The lifetime of a variable x is the portion of execution in which x is defined
  - Lifetime is a dynamic (run-time) concept
  - Scope is a static concept

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 {
 int g() { 1 };
 int f() { g() };
 int main() { g(); f(); };
}
```



Example 2

```
Class Main {
 int g(){1};
 int f(int x){
   if(x == 0) g();
   else f(x-1);
 };
 int main() {f(3);};
}
```

Poll: What is the activation tree?

```
bool isEven(int x){
  return (x % 2 == 0);
}


bool isOne(int x) {
  return (x == 1);
}

powerOfTwo(int x)  {
  if isEven(x)
    powerOfTwo(x / 2);
  else
    isOne(x);
}

main() {
 powerOfTwo(4);
}
```

Activation Trees

- 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

Activation Trees

- Example:

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

main

Stack

main

Activation Trees

- Example:

```
Class Main {
 int g() { 1 };
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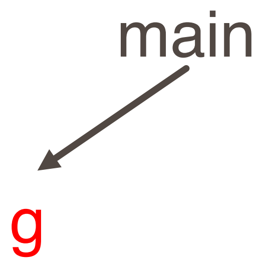


Stack

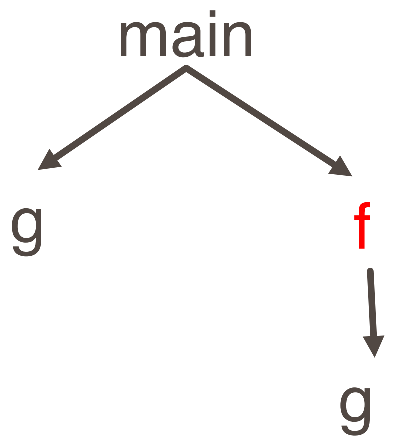
main

g

Activation Trees

- Example:

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



Stack

main

~~g~~. f

Activation Trees

- Example:

```
Class Main {
 int g() { 1 };
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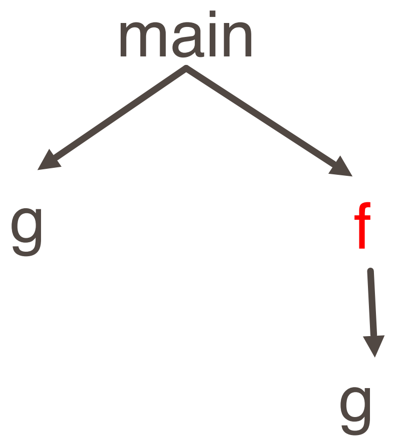
}
```



Stack

main

~~g~~ f

g

Example 2

```
Class Main {
 int g(){1};
 int f(int x){
   if(x == 0) g();
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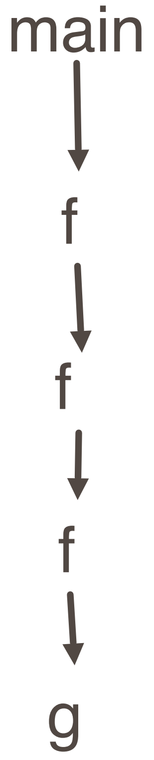
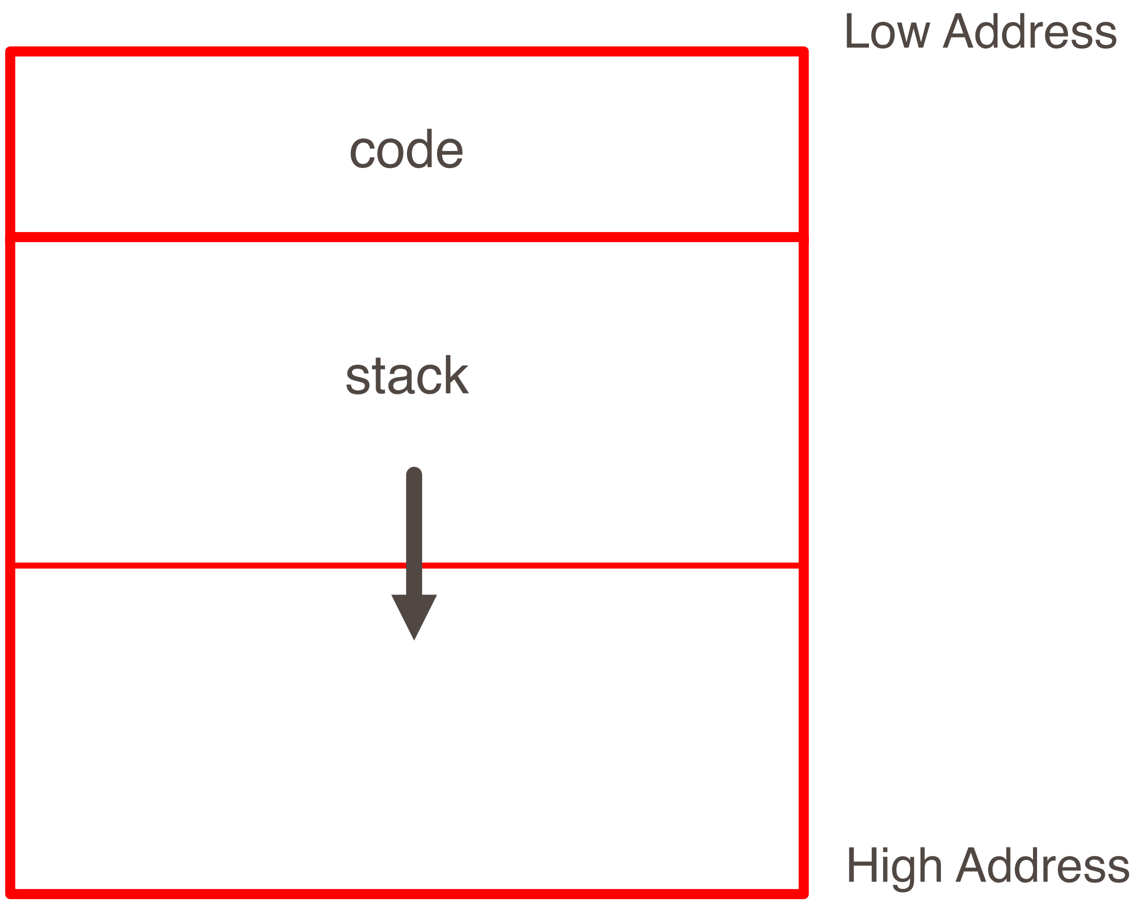
```



Revised Memory Layout



Activation Records

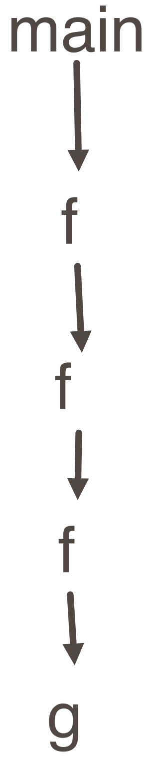
- The information needed to manage one procedure activation is called an activation record (AR) or frame.
- If procedure F calls G, then G's activation record contains a mix of info about F and G.
  - F is "suspended" until G completes, at which point F resumes.
  - G's AR contains information needed 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

Example 2

```
Class Main {
  int g(){1};
  int f(int x){
    if(x == 0) g();
    else f(x-1) (**);
  };
  int main() {f(3); (*)};
}
```



	main
(result)	f
argument=3	
control link	
return address (*)	
(result)	f
argument=2	
control link	
return address (**)	

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

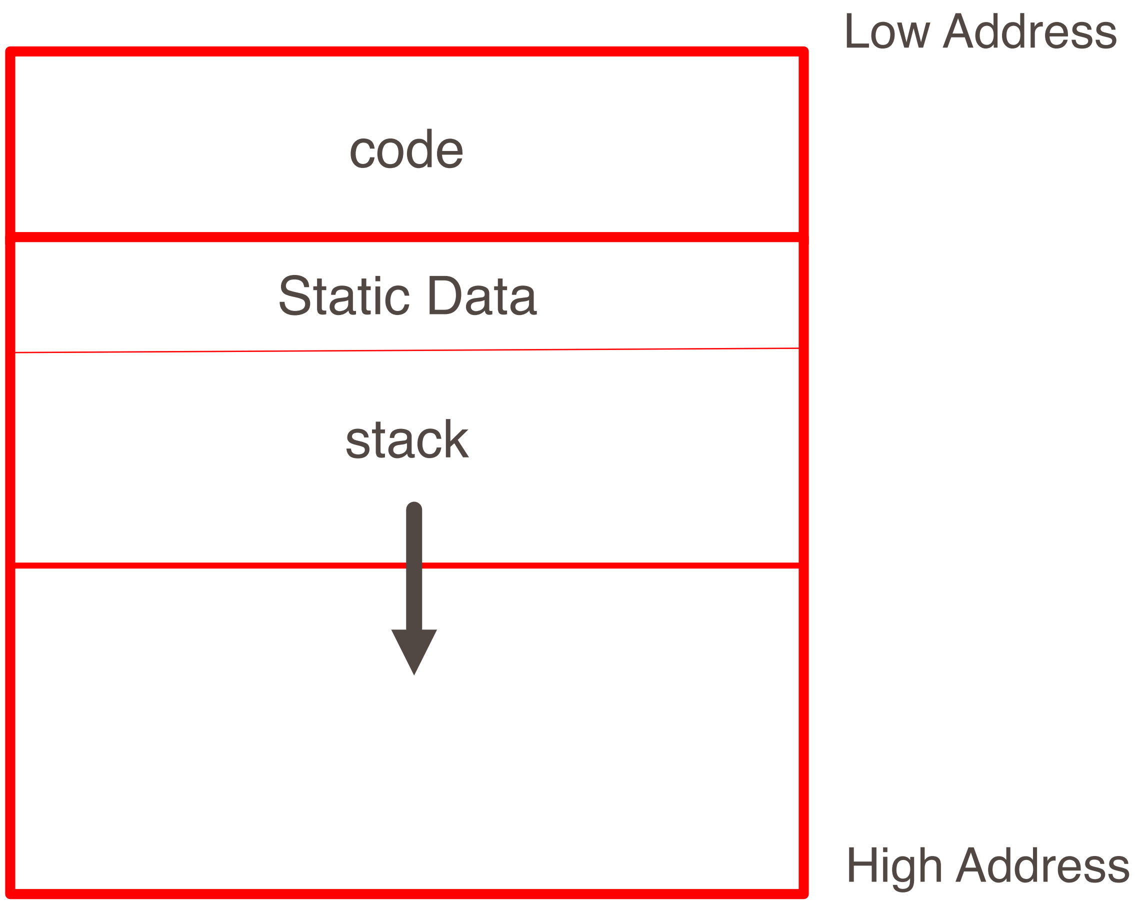
The compiler must determine, at compile-time, the layout of activation records and generate code that correctly accesses locations in the activation record

Thus, the AR layout and the code generator must be designed together.

Globals

- 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

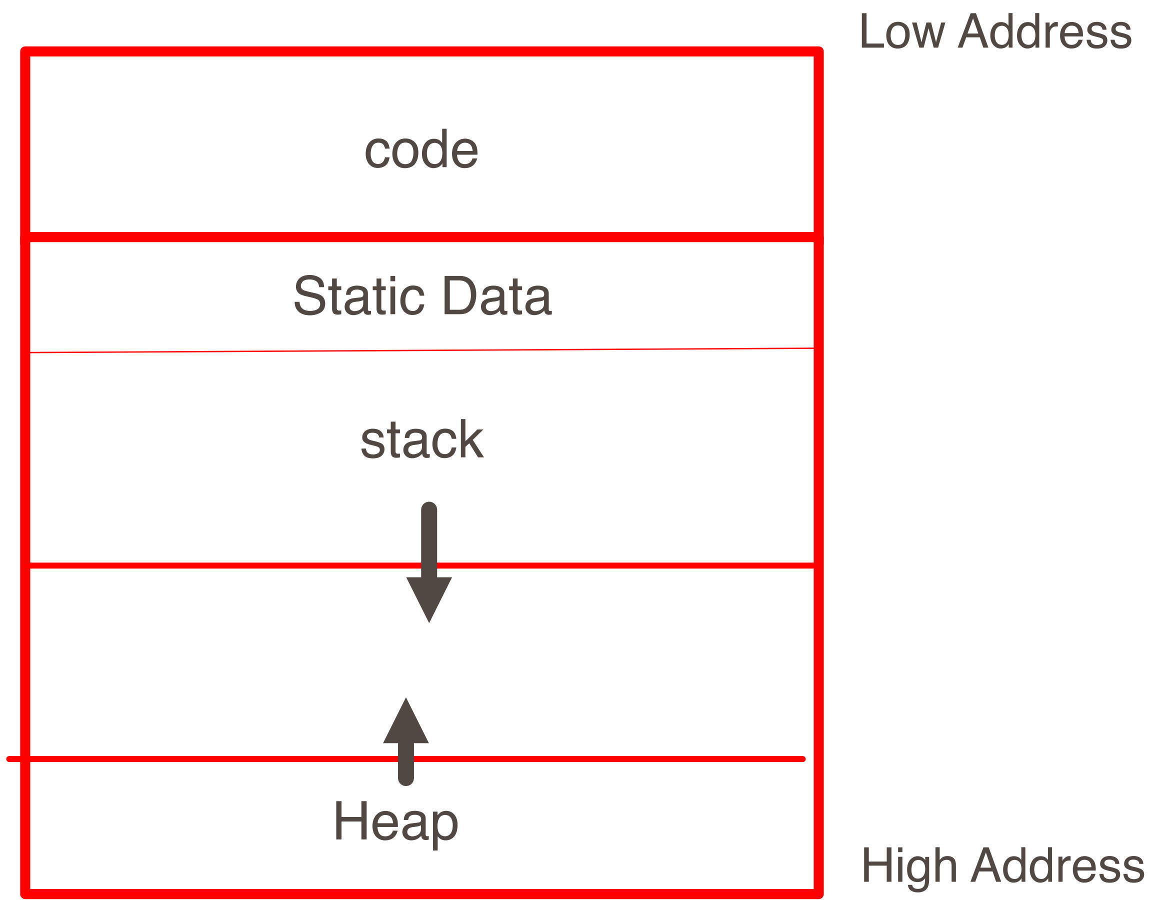
Revised Memory Layout



Heap Storage

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

Revised Memory Layout



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
- 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

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 aligned if it begins at a word boundary
- Most machines have some alignment restrictions or performance penalties for poor alignment
  - SPARC and ARM prohibit unaligned accesses
  - MIPS has special unaligned load/store instructions
  - x86, 68k run more slowly with unaligned accesses
- 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

Padding

- To avoid unaligned accesses, the C compiler pads the layout of unions and records.
- Rules:
  - Each n-byte object must start on a multiple of n bytes (no unaligned accesses).
  - Any object containing an n-byte object must be of size m*n for some integer m (aligned even when arrayed).

```
struct padded {
        int x;    /* 4 bytes */
        char z;   /* 1 byte */
        short y;  /* 2 bytes */
        char w;   /* 1 byte */
};
```

x	x	x	x
y	y		z
			w

```
struct padded {
        char a;   /* 1 byte */
        short b;  /* 2 bytes */
        short c;  /* 2 bytes */
};
```

b	b		a
		c	c

Unions

- A C struct has a separate space for each field; a C union shares one space among all fields

```
union intchar {
 int i;   /* 4 bytes */
 char c; /* 1 byte */
};
```

i	i	i	i/c

```
union twostructs {
 struct {
      char c; /* 1 byte */
      int i; /* 4 bytes */
   } a;
 struct {
      short s1; /* 2 bytes */
      short s2; /* 2 bytes */
  } b;
}
```

			c
i	i	i	i

or

s2	s2	s1	s1