Programming Languages & Translators

CODE GENERATION

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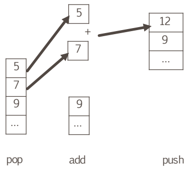
These slides are motivated from Prof. Alex Aiken: Compilers (Stanford)

Stack Machine

- 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 i on 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 ← acc + top_of_stack
  - Only one memory operation!

Stack Machine with Accumulator

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

Stack Machine with Accumulator. Example

- Compute 7 + 5 using an accumulator

1. acc ← 7; push acc
2. acc ← 5
3. acc ← acc + top_of_stack
4. pop

A Bigger Example: 3 + (7 + 5)

Code	ACC	Stack
acc ← 3	3	<init>
push acc	3	3,<init>
acc ← 7	7	3,<init>
push	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>

It is very important evaluation of a subexpression preserves the stack

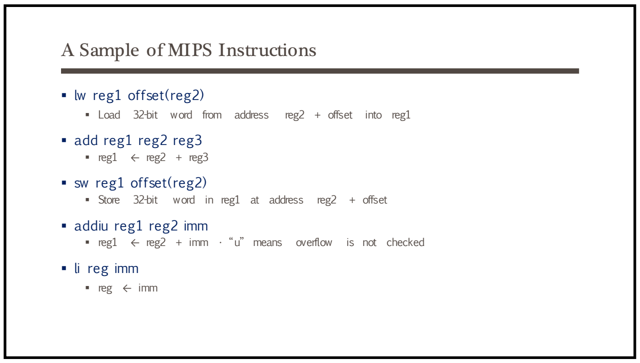
- Stack before the evaluation of 7 + 5 is 3
- Stack after the evaluation of 7 + 5 is 3
- The first operand is on top of the stack

From Stack Machines to MIPS

- The compiler generates code for a stack machine with accumulator
- Let's run the resulting code on a MIPS like processor.
  - Simulate stack machine instructions using MIPS instructions and registers
- The accumulator is kept in MIPS register $a0
- The stack is kept in memory
  - The stack grows towards lower addresses
- The address of the next location on the stack is kept in MIPS register $sp
  - The top of the stack is at address $sp + 4

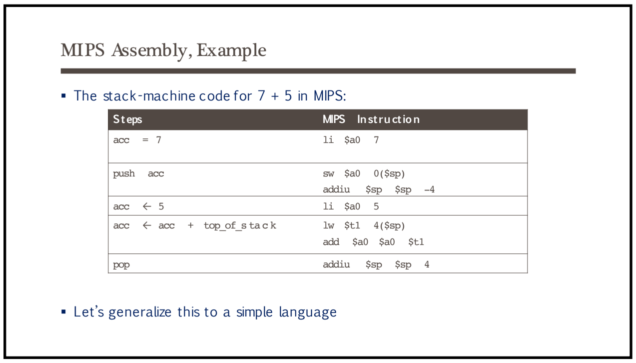
MIPS Assembly

- MIPS architecture
  - Prototypical Reduced Instruction Set Computer (RISC) architecture
  - Arithmetic operations use registers for operands and results
  - Must use load and store instructions to use operands and results in memory
  - 32 general purpose registers (32 bits each)
- We will use $sp, $a0 and $t1 (a temporary register)



A Sample of MIPS Instructions

- lw reg1 offset(reg2)
  - Load 32-bit word from address reg2 + offset into reg1
- add reg1 reg2 reg3
  - reg1 ← reg2 + reg3
- sw reg1 offset(reg2)
  - Store 32-bit word in reg1 at address reg2 + offset
- addiu reg1 reg2 imm
  - reg1 ← reg2 + imm · “u” means overflow is not checked
- li reg imm
  - reg ← imm

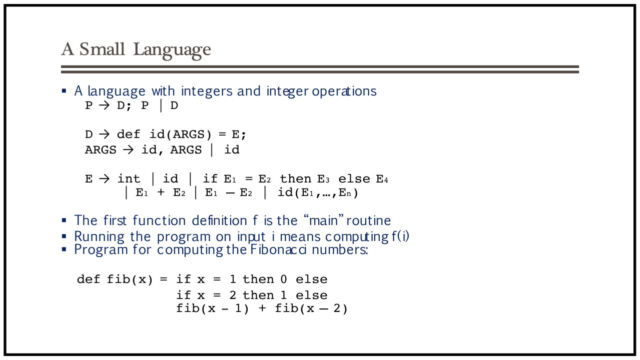


MIPS Assembly, Example

- The stack-machine code for 7 + 5 in MIPS:

Steps	MIPS Instruction
acc = 7	li $a0 7
push acc	sw $a0 0($sp) addiu $sp $sp -4
acc ← 5	li $a0 5
acc ← acc + top_of_stack	lw $t1 4($sp) add $a0 $a0 $t1
pop	addiu $sp $sp 4

- Let’s generalize this to a simple language



A Small Language

- A language with integers and integer operations

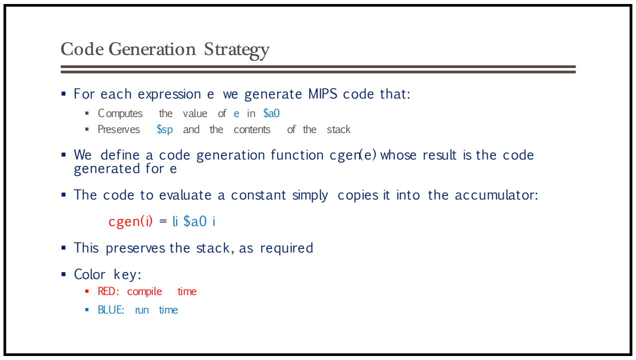
```
P → D; P | D

D → def id(ARGS) = E;
ARGS → id, ARGS | id

E → int | id | if E1 = E2 then E3 else E4
     | E1 + E2 | E1 – E2 | id(E1,…,En)
```

- The first function definition f is the “main” routine
- Running the program on input i means computing f(i)
- Program for computing the Fibonacci numbers:

```
def fib(x) = if x = 1 then 0 else
             if x = 2 then 1 else
             fib(x - 1) + fib(x – 2)
```

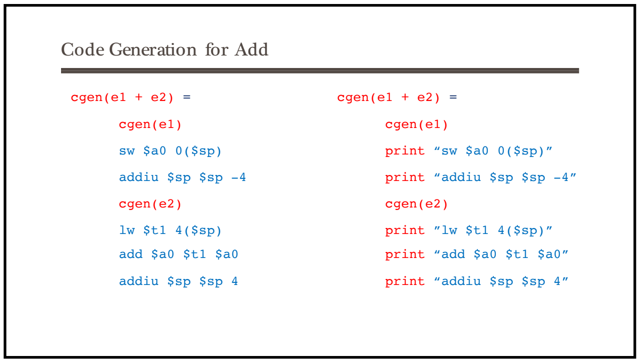


Code Generation Strategy

- For each expression e we generate MIPS code that:
  - Computes the value of e in $a0
  - Preserves $sp and the contents of the stack
- We define a code generation function cgen(e) whose result is the code generated for e
- The code to evaluate a constant simply copies it into the accumulator:

  cgen(i) = li $a0 i

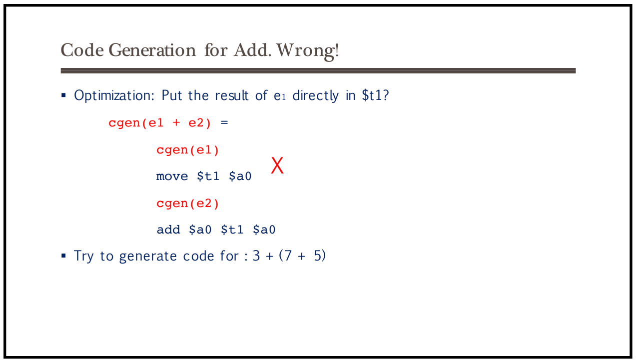
- This preserves the stack, as required
- Color key:
  - RED: compile time
  - BLUE: run time



Code Generation for Add

```
cgen(e1 + e2) =
      cgen(e1)
      sw $a0 0($sp)
      addiu $sp $sp -4
      cgen(e2)
      lw $t1 4($sp)
      add $a0 $t1 $a0
      addiu $sp $sp 4
```

```
cgen(e1 + e2) =
      cgen(e1)
      print “sw $a0 0($sp)”
      print “addiu $sp $sp -4”
      cgen(e2)
      print “lw $t1 4($sp)”
      print “add $a0 $t1 $a0”
      print “addiu $sp $sp 4”
```



Code Generation for Add. Wrong!

- Optimization: Put the result of e_1 directly in $t1?

```
cgen(e1 + e2) =
      cgen(e1)
      move $t1 $a0     X
      cgen(e2)
      add $a0 $t1 $a0
```

- Try to generate code for : 3 + (7 + 5)

Code Generation Notes

- The code for + is a template with “holes” for code for evaluating e_1 and e_2
- Stack machine code generation is recursive
  - Code for e_1 + e_2 is code for e_1 and e_2 glued together
- Code generation can be written as a recursive descent of the AST
  - At least for expressions

Code Generation for Sub and Constants

- New instruction: `sub reg1 reg2 reg3`
  - Implements `reg1 ← reg2 - reg3`

```
cgen(e1 - e2) = cgen(e1)
sw $a0 0($sp)
addiu $sp $sp -4
cgen(e2)
lw $t1 4($sp)
sub $a0 $t1 $a0
addiu $sp $sp 4
```

Code Generation for Conditional

- We need flow control instructions
- New instruction: `beq reg1 reg2 label`
  - Branch to label if reg1 = reg2
- New instruction: `b label`
  - Unconditional jump to label

Code Generation for If (Cont.)

```
cgen(if e1 = e2 then e3 else e4) =
      cgen(e1)
      sw $a0 0($sp)
      addiu $sp $sp -4
      cgen(e2)
      lw $t1 4($sp)
      addiu $sp $sp 4
      beq $a0 $t1 true_branch
```

```
false_branch:
 cgen(e4)
 b end_if
true_branch:
 cgen(e3)
end_if:
```

The Activation Record

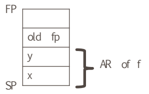
- Code for function calls and function definitions depends on the layout of the AR
- A very simple AR suffices for this language:
  - The result is always in the accumulator
    - No need to store the result in the AR
  - The activation record holds actual parameters
    - For $f(x_1,\ldots,x_n)$ push $x_n,\ldots,x_1$ on the stack
    - These are the only variables in this language

The Activation Record (Cont.)

- The stack discipline guarantees that on function exit $sp is the same as it was on function entry
  - No need for a control link
- We need the return address
- A pointer to the current activation is useful
  - This pointer lives in register $fp (frame pointer)
  - Reason for frame pointer will be clear shortly

The Activation Record

- Summary: For this language, an AR with the caller's frame pointer, the actual parameters, and the return address suffices
- Picture: Consider a call to f(x,y), the AR is:



Code Generation for Function Call

- The calling sequence is the instructions (of both caller and callee) to set up a function invocation
- New instruction: jal label
  - Jump to label, save address of next instruction in $ra
  - On other architectures the return address is stored on the stack by the "call" instruction

Code Generation for Function Call (Cont.)

```
cgen(f(e1,…,en)) =
      sw $fp 0($sp)
      addiu $sp $sp -4
      cgen(en)
      sw $a0 0($sp)
      addiu $sp $sp -4
      …
      cgen(e1)
      sw $a0 0($sp)
      addiu $sp $sp -4
      jal f_entry
```

- The caller saves its value of the frame pointer
- Then it saves the actual parameters in reverse order
- The caller saves the return address in register $ra
- The AR so far is 4*n+4 bytes long

Code Generation for Function Definition

- New instruction: jr reg
  - Jump to address in register reg

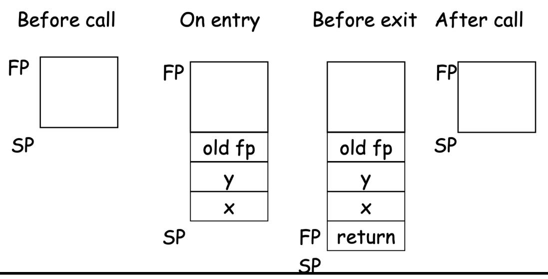
```
cgen(def f(x1,…,xn) = e) =
f_entry:
  move $fp $sp
  sw $ra 0($sp)
  addiu $sp $sp -4
  cgen(e)
  lw $ra 4($sp)
  addiu $sp $sp z
  lw $fp 0($sp)
  jr $ra
```

Note: The frame pointer points to the top, not bottom of the frame

The callee pops the return address, the actual arguments and the saved value of the frame pointer.

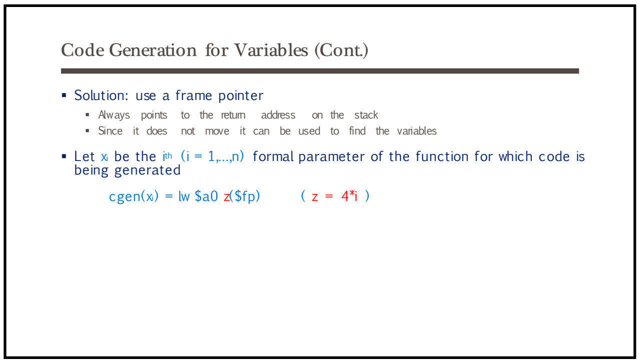
z = 4*n + 8 (return address, old frame pointer)

Calling Sequence: Example for f(x,y)



Code Generation for Variables

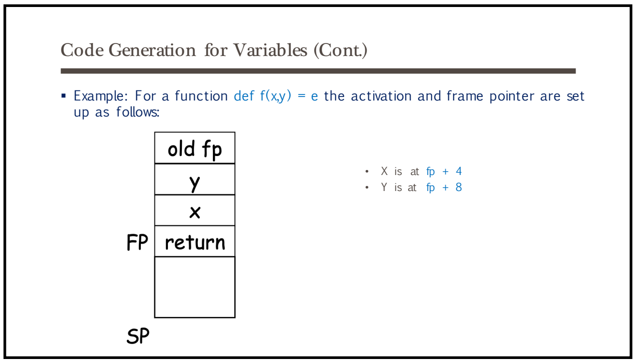
- Variable references are the last construct
- The "variables" of a function are just its parameters
  - They are all in the AR
  - Pushed by the caller
- Problem: Because the stack grows when intermediate results are saved, the variables are not at a fixed offset from $sp



Code Generation for Variables (Cont.)

- Solution: use a frame pointer
  - Always points to the return address on the stack
  - Since it does not move it can be used to find the variables
- Let x_i be the i^{th} (i = 1,…,n) formal parameter of the function for which code is being generated

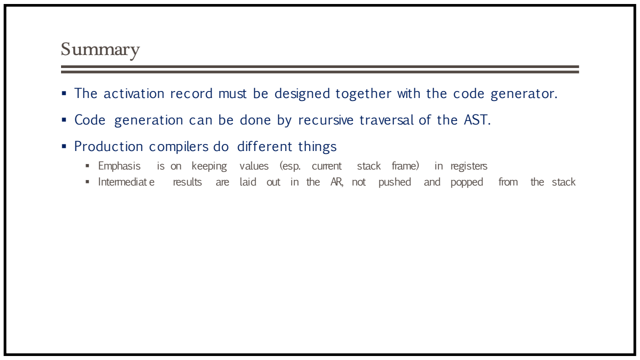
cgen(x) = lw $a0 z($fp)   (z = 4*i)



Code Generation for Variables (Cont.)

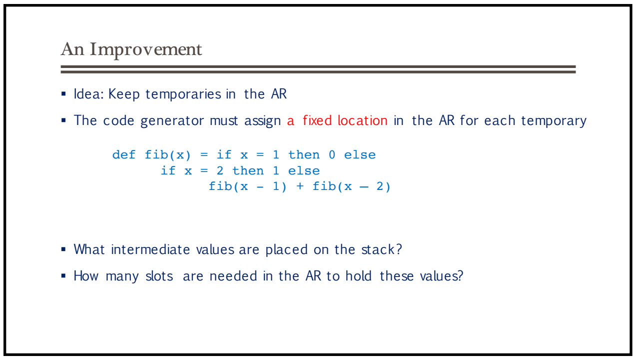
- Example: For a function def f(x,y) = e the activation and frame pointer are set up as follows:

- X is at fp + 4
- Y is at fp + 8



Summary

- The activation record must be designed together with the code generator.
- Code generation can be done by recursive traversal of the AST.
- Production compilers do different things
  - Emphasis is on keeping values (esp. current stack frame) in registers
  - Intermediate results are laid out in the AR, not pushed and popped from the stack

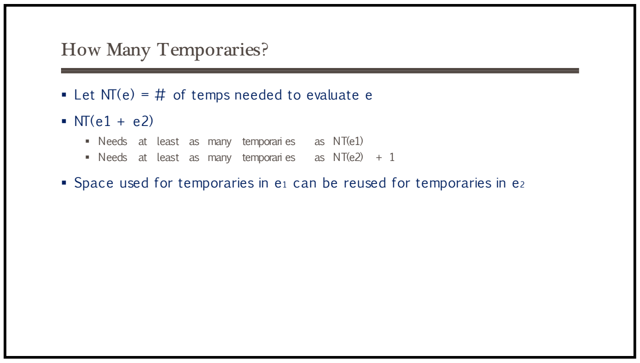


An Improvement

- Idea: Keep temporaries in the AR
- The code generator must assign a fixed location in the AR for each temporary

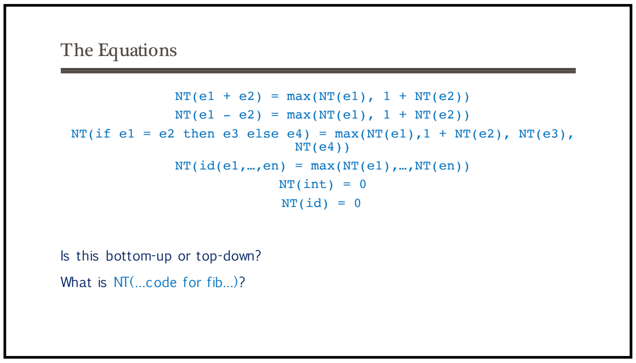
```
def fib(x) = if x = 1 then 0 else
       if x = 2 then 1 else
             fib(x - 1) + fib(x – 2)
```

- What intermediate values are placed on the stack?
- How many slots are needed in the AR to hold these values?



How Many Temporaries?

- Let NT(e) = # of temps needed to evaluate e
- NT(e1 + e2)
  - Needs at least as many temporaries as NT(e1)
  - Needs at least as many temporaries as NT(e2) + 1
- Space used for temporaries in e_1 can be reused for temporaries in e_2



The Equations

```
              NT(e1 + e2) = max(NT(e1), 1 + NT(e2))
              NT(e1 - e2) = max(NT(e1), 1 + NT(e2))
NT(if e1 = e2 then e3 else e4) = max(NT(e1),1 + NT(e2), NT(e3),
                                 NT(e4))
              NT(id(e1,…,en) = max(NT(e1),…,NT(en))
                           NT(int) = 0
                           NT(id) = 0
```

Is this bottom-up or top-down?

What is NT(…code for fib…)?

The Revised AR

- For a function definition $f(x_1,\ldots,x_n) = e$ the AR has $2 + n + NT(e)$ elements
  - Return address
  - Frame pointer
  - n arguments
  - NT(e) locations for intermediate results

Old FP
x_n
. . .
x_1
Return Addr.
Temp NT(e)
. . .
Temp 1

Revised Code Generation

- Code generation must know how many temporaries are in use at each point
- Add a new argument to code generation: the position of the next available temporary

Code Generation for +

- Original

```
cgen(e1 + e2) =
      cgen(e1)
      sw $a0 0($sp)
      addiu $sp $sp -4
      cgen(e2)
      lw $t1 4($sp)
      add $a0 $t1 $a0
      addiu $sp $sp 4
```

- Revised

```
cgen(e1 + e2, nt) =
      cgen(e1, nt)
      sw $a0 nt($fp)
      cgen(e2, nt + 4)
      lw $t1 nt($fp)
      add $a0 $t1 $a0
```

The temporary area is used like a small, fixed size stack

CODE GENERATION FOR OO LANGUAGES

Object Layout

- OO implementation = Stuff from last part + more stuff
- OO Slogan: If B is a subclass of A, than an object of class B can be used wherever an object of class A is expected
- This means that code in class A works unmodified for an object of class B
- Two issues
  - How are objects represented in memory?
  - How is dynamic dispatch implemented?

Object Layout Example

```
Class A {
  a: Int <- 0;
  d: Int <- 1;
  f(): Int { a <- a + d };
};
```

```
Class B inherits A {
   b: Int <- 2;
   f(): Int { a };
   g(): Int { a <- a - b };
};
```

```
Class C inherits A {
  c: Int <- 3;
  h(): Int { a <- a * c };
};
```

Object Layout (Cont.)

- Attributes a and d are inherited by classes B and C
- All methods in all classes refer to a
- For A methods to work correctly in A, B, and C objects, attribute a must be in the same "place" in each object.
- An object is like a struct in C. The reference foo.field is an index into a foo struct at an offset corresponding to field

Subclasses

Observation: Given a layout for class A, a layout for subclass B can be defined by extending the layout of A with additional slots for the additional attributes of B

Leaves the layout of A unchanged (B is an extension)

Layout Picture

Offset Class	0	4	8	12	16	20
A	Atag	5	*	a	d	
B	Btag	6	*	a	d	b
C	Ctag	6	*	a	d	c

Dynamic Dispatch

- Consider the following dispatches (using the same example)
- e.g()
    - g refers to method in B if e is a B
- e.f()
    - f refers to method in A if f is an A or C (inherited in the case of C)
    - f refers to method in B for a B object
- The implementation of methods and dynamic dispatch strongly resembles the implementation of attributes

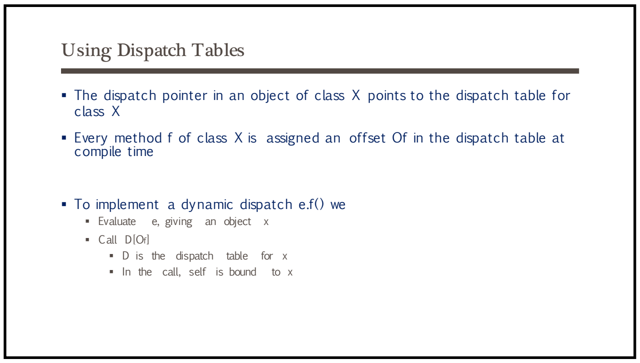
Dispatch Tables

- Every class has a fixed set of methods (including inherited methods)
- A dispatch table indexes these methods
    - An array of method entry points
    - A method f lives at a fixed offset in the dispatch table for a class and all of its subclasses

Dispatch Table Example

Offset Class	0	4
A	fA	
B	fB	g
C	fA	h

- The dispatch table for class A has only 1 method
- The tables for B and C extend the table for A to the right
- Because methods can be overridden, the method for f is not the same in every class, but is always at the same offset



Using Dispatch Tables

- The dispatch pointer in an object of class X points to the dispatch table for class X
- Every method f of class X is assigned an offset Of in the dispatch table at compile time
- To implement a dynamic dispatch e.f() we
  - Evaluate e, giving an object x
  - Call $D[O_f]$
    - D is the dispatch table for x
    - In the call, self is bound to x