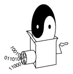

CS 412
Introduction to Compilers

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Lecture 18: Finishing code generation
9 Mar 01

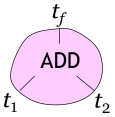
Outline

- Tiling as syntax-directed translation
- Implementing function calls
- Implementing functions
- Optimizing away the frame pointer
- Dynamically-allocated structures: strings and arrays
- Register allocation the easy way

Tiling, formally

- Each tile is really an inference rule!
- Write $e \Rightarrow c\ (\text{reg } t)$
  for "c is valid code for IR expression e that puts result into t"
- Write $s \Rightarrow c$
  for "c is valid code for IR statement s"
- Translation is not a function of e/s : many possible translations (unlike $\mathcal{T}[\![e]\!]$, $\mathcal{S}[\![e]\!]$, etc.)
  - translation *relation* generalizes translation function
  - can apply to earlier translations too – but less payoff

Expression tile as rule

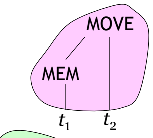


mov t_f, t_1
add t_f, t_2

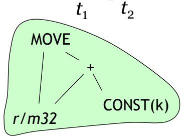
$$\frac{\begin{array}{c} e_1 \Rightarrow c_1\ (\text{reg } t_1) \\ e_2 \Rightarrow c_2\ (\text{reg } t_2) \end{array}}{\text{ADD}(e_1, e_2) \Rightarrow c_1;\ c_2;\ \texttt{mov}\ t_f,\ t_1;\ \texttt{add}\ t_f,\ t_2\ \ (\text{reg } t_f)}$$

Statement tiles as rules

$$\frac{\begin{array}{c} e_1 \Rightarrow c_1\ (\text{reg } t_1) \\ e_2 \Rightarrow c_2\ (\text{reg } t_2) \end{array}}{\begin{array}{l} \text{MOVE}(\text{MEM}(e_1), e_2) \Rightarrow \\ \quad c_1 ; c_2 ; \texttt{mov [}t_1\texttt{], } t_2 \end{array}}$$



$$\frac{e_1, e_2 \Rightarrow op_1\ (\text{r/m32})}{\text{MOVE}(e_1, e_2 + \text{CONST}(k)) \Rightarrow \texttt{add}\ op_1,\ k}$$



Inference rules are *not* syntax-directed – need heuristic or dynamic programming to choose

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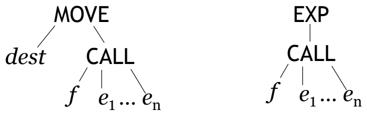
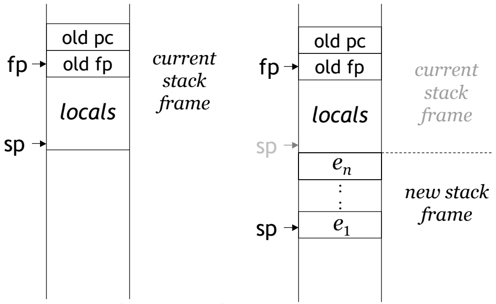
Function calls

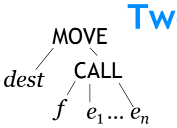
- How to generate code for function calls?
- Two kinds of IR statements in canonical form

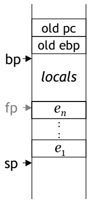


Stack layout



Two translations





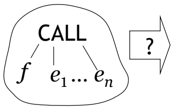
non-RISC

```
push eₙ
…
push e₁
call f
mov dest, eax
add esp, 4*n
```

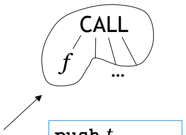
RISC

```
sub esp, 4*n
mov [esp + 4], e₁
...
mov [esp + 4*n], eₙ
call f
mov dest, eax
add esp, 4*n
```

Tiling a call



```
push eₙ
…
push e₁
call f
mov dest, eax
add esp, 4*n
```



```
push tₙ
…
push t₁
call f
mov dest, eax
add esp, 4*n
```

- Approach 1: don't fold e_i into tile
- Downside: generates a lot of extra temporaries
- Approach 2: try to match e_i against r/m32, tile e_i separately if failure

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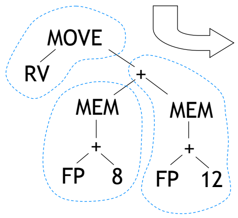
Compiling function bodies

- How we compiled function body:
  $\mathcal{S}[\![f(\ldots) : T = e]\!]$ = SEQ(MOVE(RV, $\mathcal{E}[\![e]\!]$),
  LABEL(*epilogue*))
  $\mathcal{S}[\![f(\ldots) = e]\!]$ = SEQ(EXP($\mathcal{E}[\![e]\!]$),
  LABEL(*epilogue*))
- Variables:
  $\mathcal{E}[\![v]\!]$ = TEMP(t_v) for locals
  $\mathcal{E}[\![v]\!]$ = MEM(TEMP(FP) + (4*i+4)) for arg. i
  $\mathcal{E}[\![v]\!]$ = MEM(NAME(v)) for globals
- Try it out:
  f(x: int, y:int) = x + y

Abstract assembly for f

f(x: int, y:int) = x + y

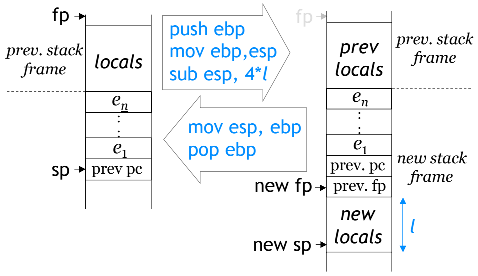


```
mov t1, [ebp+8]
mov t2, t1
add t2, [ebp+12]
mov eax, t2
```

What's missing here?

Stack frame setup

- Need code to set up stack frame on entry



```
push ebp
mov ebp,esp
sub esp, 4*l
```

```
mov esp, ebp
pop ebp
```

Function code

```
f: push ebp
   mov ebp,esp
   sub esp, 4*l
   mov t1, [ebp+8]
   mov t2, t1
   add t2, [ebp+12]
   mov eax, t2
f_epilogue:
   mov esp, ebp
   pop ebp
   ret
```

function *prologue*

function *epilogue*

The Glory of CISC

```
f:  push ebp
    mov ebp,esp
    sub esp, 4*l
    mov t1, [ebp+8]
    mov t2, t1
    add t2, [ebp+12]
    mov eax, t2
f_epilogue:
    mov esp, ebp
    pop ebp
    ret
```

```
enter 4*l, 0
```

```
f_epilogue:
    leave
    ret
```

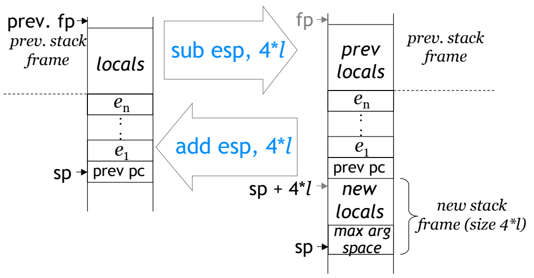
Calling conventions

- Have described standard C calling convention
  - arguments pushed on stack, in reverse order
  - caller cleans up arguments
- stdcall: callee cleans up. MIPS/Alpha: first 4/6 arguments passed in registers
- Choice of caller- vs. callee-save:
  - caller-save: caller must save registers if needed after call; usable freely (**e[acd]x**)
  - callee-save: function not allowed to change; to use, must be saved (**e[sd]i**, **e[sb]p**, **ebx**)

Optimizing away ebp

- No need for frame pointer register!
- Idea: maintain constant offset *k* between frame pointer and stack pointer
  - Use RISC-style argument passing rather than pushing arguments on stack
  - All references to MEM(FP+*n*) translated to operand `[esp+(n+k)]` instead of to `[ebp+n]`
- Advantage: get whole extra register to use when allocating registers (7!)

Stack frame setup



Caveats

- Get even faster (and RISC-core) prologue and epilogue than with **enter/leave** but:
- To avoid breaking callers, must save **ebp** register if we want to use it (callee-save)
- Doesn't work if stack frame is truly variable-sized
  - alloca(*n*) call in C allocates *n* bytes *on the stack* – compiler cannot predict
  - not a problem in Iota: arrays heap-allocated, stack frame has constant size

Dynamic structures

- Modern programming languages allow dynamically allocated data structures: strings, arrays, objects

C: char *x = (char *)malloc(strlen(s) + 1);

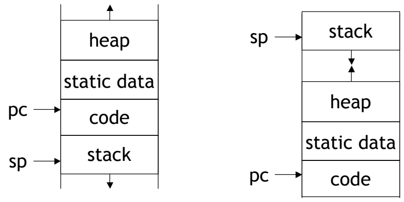
C++: Foo *f = new Foo(…);

Java: Foo f = new Foo(…);
String s = s1 + s2;

Iota: x: array[int] = new int[5] (0);
String s = s1 + s2;

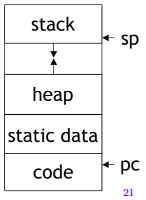
Program Heap

- Program has 4 memory areas: code segment, stack segment, static data, heap
- Two typical virtual memory layouts (depends on OS):

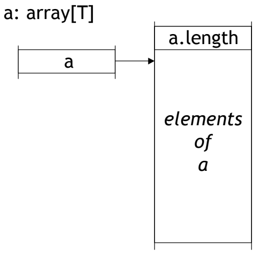


Object allocation

- Dynamic objects allocated in the heap
  - array creation, string concatenation
  - malloc(*n*) returns new chunk of *n* bytes, free(*x*) releases memory starting at *x*
- Globals statically allocated in data segment
  - global variables
  - string constants
  - assembler supports data segment declarations



Iota dynamic structures



new *T* [*n*] (*e*)

⇩

a = malloc(4*n + 4);
MEM(a) = n;
a = a + 4;
a_1 = a; a_2 = a + 4*n;
while (a_1 != a_2)
(MEM(a_1) = $\mathcal{E}[\![e]\!]$;
a_1 = a_1 + 4);
a

- PA4: We give you newarray, newstring calls with garbage collection support (no free call needed)

Trivial register allocation

- Can convert abstract assembly to real assembly easily (but generate bad code)
- Allocate every temporary to location in the current stack frame rather than to a register
- Every temporary stored in different place -- no possibility of conflict
- Three registers needed to shuttle data in and out of stack frame (max. # registers used by one instruction) : *e.g*, eax, ecx, edx

Rewriting abstract code

- Given instruction, replace every temporary in instruction with one of three registers `e[acd]x`
- Add mov instructions before instruction to load registers properly
- Add mov instructions after instruction to put data back onto stack (if necessary)

push t1 ⇒ mov eax, [fp - t1off]; push eax
mov [fp+4], t3 ⇒ ?
add t1, [fp - 4] ⇒ ?

Result

- Simple way to get working code
- Code is longer than necessary, slower
- Also can allocate temporaries to registers until registers run out (3 temporaries on Pentium, 20+ on MIPS, Alpha)
- Code generation technique actually used by some compilers when all optimization turned off (-O0)
- Will use for Programming Assignment 4

Summary

- Complete code generation technique
- Use tiling to perform instruction selection
- Arguments mapped to stack locations, locals to temporaries
- Function code generated by gluing prologue, epilogue onto body
- Dynamic structure allocation handled by relying on heap allocation routines (`malloc`)
- Static structures allocated by data segment assembler declarations
- Allocate temporaries to stack locations to eliminate use of unbounded # of registers
- Shuttle temporaries in and out using `e[acd]x` regs

Where we are