CS4410 : Spring 2013

Simple Code Generation

Code Generation

- Next PS: Map Fish code to MIPS code
- Issues:
  - eliminating compound expressions
  - eliminating variables
  - encoding conditionals, short-circuits, loops

Source

```
type exp =
   Var of var
| Int of int
| Binop of exp * binop * exp
| Not of exp
| Or of exp * exp
| And of exp * exp
| Assign of var * exp
```

Target: MIPS

```
type label = string

type reg =
  R0 | R1 | R2 | … | R31

type operand =
   Reg of reg
| Immed of word
```

MIPS continued

```
type inst =
    Add of reg * reg * operand
  | Li of reg * word
  | Slt of reg * reg * operand
  | Beq of reg * reg * label
  | Bgez of reg * label
  | J of label
  | La of reg * label
  | Lw of reg * reg * word
  | Sw of reg * reg * word
  | Label of label | ...
```

Variables

Fish only has global variables.

These can be placed in the *data segment*.

```
.data
.align 0
x:  .word 0
y:  .word 0
z:  .word 0
```

Variable Access

To compile **`x = x+1`**

```
la $3, x        ;   load x's address
lw $2, 0($3)    ;   load x's value
addi $2,$2,1    ;   add 1
sw $2, 0($3)    ;   store value in x
```

First Problem: Nested Expr's

- Source:
  - Binop(Binop(x,Plus,y),Plus,Binop(w,Plus,z))
- Target:
  - add rd, rs, rt

What should we do?

A Simple Strategy

- Given: Binop(A,Plus,B)
- translate A so that result ends up in a particular register (e.g., $3)
- translate B so that result ends up in a different register (e.g., $2)
- Generate: add $2, $3, $2

Problems?

Strategy Fixed:

- Invariants:
  - results always placed in $2
- Given: Binop(A,Plus,B)
- translate A
- save $2 somewhere
- translate B
- Restore A's value into register $3
- Generate: add $2, $3, $2

For example:

Binop(Binop(x,Plus,y),Plus,Binop(w,Plus,z))

1. compute x+y, placing result in $2
2. store result in a temporary t1
3. compute w+z, placing result in $2
4. load temporary t1 into a register, say $3
5. add $2, $3, $2

Expression Compilation

```
let rec exp2mips(i:exp):inst list =
    match i with
    | Int j -> [Li(R2, Word32.fromInt j)]
    | Var x -> [La(R2,x), Lw(R2,R2,zero)]
    | Binop(i1,b,i2) ->
      (let t = new_temp()in
          (exp2mips i1) @ [La(R1,t), Sw(R2,R1,zero)]
        @(exp2mips i2) @ [La(R1,t), Lw(R1,R1,zero)]
        @(match b with
            Plus -> [Add(R2,R2,Reg R1)]
          | ... -> ...))
    | Assign(x,e) =>  [exp2mips e] @
                      [La(R1,x), Sw(R2,R1,zero)]
```

Statements

```
let rec stmt2mips(s:stmt):inst list =
   match s with
    | Exp e ->
        exp2mips e
    | Seq(s1,s2) ->
        (stmt2mips s1) @ (stmt2mips s2)
    | If(e,s1,s2) ->
      (let else_l = new_label() in
       let end_l = new_label() in
       (exp2mips b) @ [Beq(R2,R0,else_l)] @
       (stmt2mips s1) @ [J end_l,Label else_l] @
       (stmt2mips s2) @ [Label end_l])
```

Statements Continued

```
| While(e,s) ->
    (let test_l = new_label() in
     let top_l = new_label() in
       [J test_l, Label top_l] @
       (stmt2mips s) @
       [Label test_l] @
       (exp2mips b) @
       [Bne(R2,R0,top_l)])
| For(e1,e2,e3,s) ->
   stmt2mips(Seq(Exp e1,While(e2,Seq(s,Exp e3))))
```

Lots of Inefficiencies:

- Compiler takes $O(n^2)$ time due to @.
- No constant folding.
- For "**`if (x == y) s1 else s2`**" we do a **`seq`** followed by a **`beq`** when we could just do a beq.
- For "**`if (b1 && b2) s1 else s2`**" we could just jump to **`s2`** when **`b1`** is false.
- Lots of **`la/lw`** and **`la/sw`** for variables.
- For **`e1 + e2`**, we always write out **`e1`**'s value to memory when we could just cache it in a register.

Append:

Naïve append:

```
fun append nil y = y
  | append (h::t) y = h::(append t y)
```

Tail-recursive append:

```
fun revapp nil y = y
  | revapp (h::t) y = revapp t (h::y)
fun rev x = revapp x []
fun append x y = revapp (rev x) y
```

Accumulater-Based:

```
let rec exp2mips'(i:exp) (a:inst list):inst list =
 match i with
   ...

let exp2mips (i:exp) = (exp2mips' i [])
```

Constant Folding: Take 1

```
let rec exp2mips'(i:F.iexp) (a:inst list) =
 match i with
    Int w -> Li(R2, Word32.fromInt w) :: a
  | Binop(i1,Plus,Int 0) -> exp2mips' i1 a
  | Binop(Int i1,Plus,Int i2) ->
      exp2mips' (Int (i1+i2)) a
  | Binop(Int i1,Minus,Int i2) ->
      exp2mips' (Int (i1-i2)) a
  | Binop(b,i1,i2) -> ...
```

Why isn't this great? How can we fix it?

Conditional Contexts

Consider: if (x < y) then S1 else S2

```
        slt  $2, $2, $3
        beq $2, ELSE
         S1
        j END
ELSE:
        S2
END:
```

Observation

- In most contexts, we want a value.
- But in a testing context, we jump to one place or another based on the value, and otherwise never use the value.
- In many situations, we can avoid materializing the value and thus produce better code.

For Example:

```
let rec bexp2mips(e:exp) (t:label) (f:label) =
  match e with
    Int 0 -> [J f]
  | Int _ -> [J t]
  | Binop(e1,Eq,e2) =>
    (let t = temp()
     in
       (exp2mips e1) @
       [La(R1,t), Sw(R2,R1,zero)] @
       (exp2mips e2) @
       [La(R1,t), Lw(R1,R1,zero),
        Bne(R1,R2,f), J t])
  | _ -> (exp2mips e1) @ [ Beq(R2,R0,f), J t ]
```

Global Variables:

We treated all variables (including temps) as if they were globals:

- set aside data with a label
- to read: load address of label, then load value stored at that address.
- to write: load address of label, then store value at that address.

This is fairly inefficient:

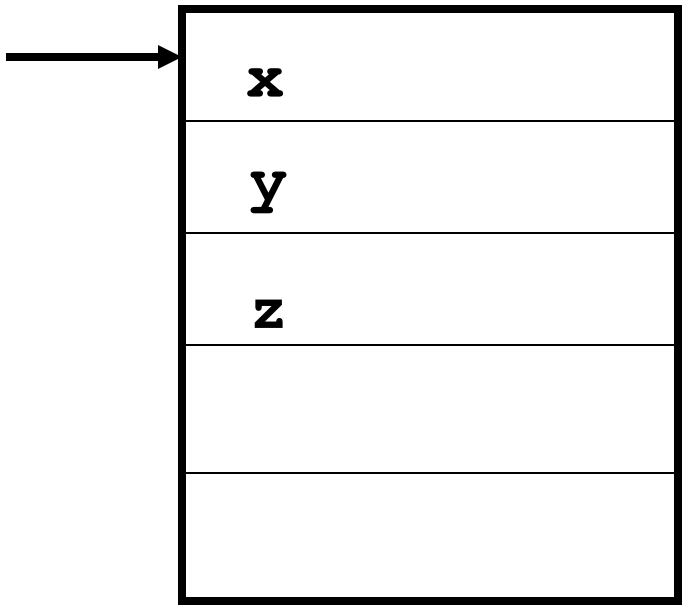
- e.g., x+x involves loading x's address twice!
- lots of memory operations.

Register Allocation:

- One option is to allocate a register to hold a variable's value:
  - Eliminates the need to load an address or do memory operations.
  - Will talk about more generally later.
  - Of course, in general, we can't avoid it when code has more (live) variables than registers.
- Can we at least avoid loading addresses?

Frames:

- Set aside one block of memory for all of the variables.
- Dedicate $30 (aka $fp) to hold the base address of the block.
- Assign each variable a position within the block (x→0, y→4, z→8, etc.)
- Now loads/stores can be done relative to $fp:



Before and After:

```
z = x+1
```

```
lda $1,x
lw  $2,0($1)
addi $2,$2,1
lda $1,z
sw  $2,0($1)
```

```
lw $2,0($fp)
addi $2,$2,1
sw $2,8($fp)
```

Lowering

- Get rid of nested expressions before translating
  - Introduce new variables to hold intermediate results
  - Perhaps do things like constant folding
- For example, **`a = (x + y) + (z + w)`** might be translated to:

```
t0 := x + y;
t1 := z + w;
a := t0 + t1;
```

12 instructions (9 memory)

```
t0 := x + y;          lw $v0, <xoff>($fp)
                      lw $v1, <yoff>($fp)
                      add $v0, $v0, $v1
                      sw $v0, <t0off>($fp)
t1 := z + w;          lw $v0, <zoff>($fp)
                      lw $v1, <woff>($fp)
                      add $v0, $v0, $v1
                      sw $v0, <t1off>($fp)
a := t0 + t1;         lw $v0, <t0off>($fp)
                      lw $v1, <t1off>($fp)
                      add $v0, $v0, $v1
                      sw $v0, <aoff>($fp)
```

Still…

We're doing a lot of stupid loads and stores.

- We shouldn't need to load/store from temps!
- (Nor variables, but we'll deal with them later…)

So another idea is to use registers to hold the intermediate values instead of variables.

- Of course, we can only use registers to hold some number of temps (say k).
- Maybe use registers to hold first k temps?

For example:

```
t0 := x;          # load variable
t1 := y;          # load variable
t2 := t0 + t1;    # add
t3 := z;          # load variable
t4 := w;          # load variable
t5 := t3 + t4;    # add
t6 := t2 + t5;    # add
a := t6;          # store result
```

Then: 8 instructions (5 mem!)

- Notice that each little statement can be directly translated to MIPs instructions:

```
t0 := x;          -->  lw $t0,<xoff>($fp)
t1 := y;          -->  lw $t1,<yoff>($fp)
t2 := t0 + t1;    -->  add $t2,$t0,$t1
t3 := z;          -->  lw $t3,<zoff>($fp)
t4 := w;          -->  lw $t4,<woff>($fp)
t5 := t3 + t4;    -->  add $t5,$t3,$t4
t6 := t2 + t5;    -->  add $t6,$t2,$t5
a := t6;          -->  sw $t6,<aoff>($fp)
```

Recycling:

- Sometimes we can recycle a temp:

```
t0 := x;              t0 taken
t1 := y;              t0,t1 taken
t2 := t0 + t1;        t2 taken (t0,t1 free)
t3 := z;              t2,t3 taken
t4 := w;              t2,t3,t4 taken
t5 := t3 + t4;        t2,t5 taken (t3,t4 free)
t6 := t2 + t5;        t6 taken (t2,t5 free)
a := t6;              (t6 free)
```

Tracking Available Temps:

Hmmm. Looks a lot like a stack…

```
t0 := x;              t0
t1 := y;              t1,t0
t0 := t0 + t1;        t0
t1 := z;              t1,t0
t2 := w;              t2,t1,t0
t1 := t1 + t2;        t1,t0
t1 := t0 + t1;        t1
a := t1;              <empty>
```

Finally, consider:

```
(x+y)*x

t0 := x;          # loads x
t1 := y;
t0 := x+y
t1 := x;          # loads x again!
t0 := t0*t1;
```

Good Compilers: (not this proj!)

Introduces temps as described earlier:

- It lowers the code to something close to assembly, where the number of resources (i.e., registers) is made explicit.
- Ideally, we have a 1-to-1 mapping between the lowered intermediate code and assembly code.

Performs an analysis to calculate the *live range* of each temp:

- A temp **`t`** is live at a program point if there is a subsequent read (use) of t along some control-flow path, without an intervening write (definition).
- The problem is simplified for *functional* code since variables are never re-defined.

Interference Graphs:

From the live-range information for each temp, we calculate an *interference graph*.

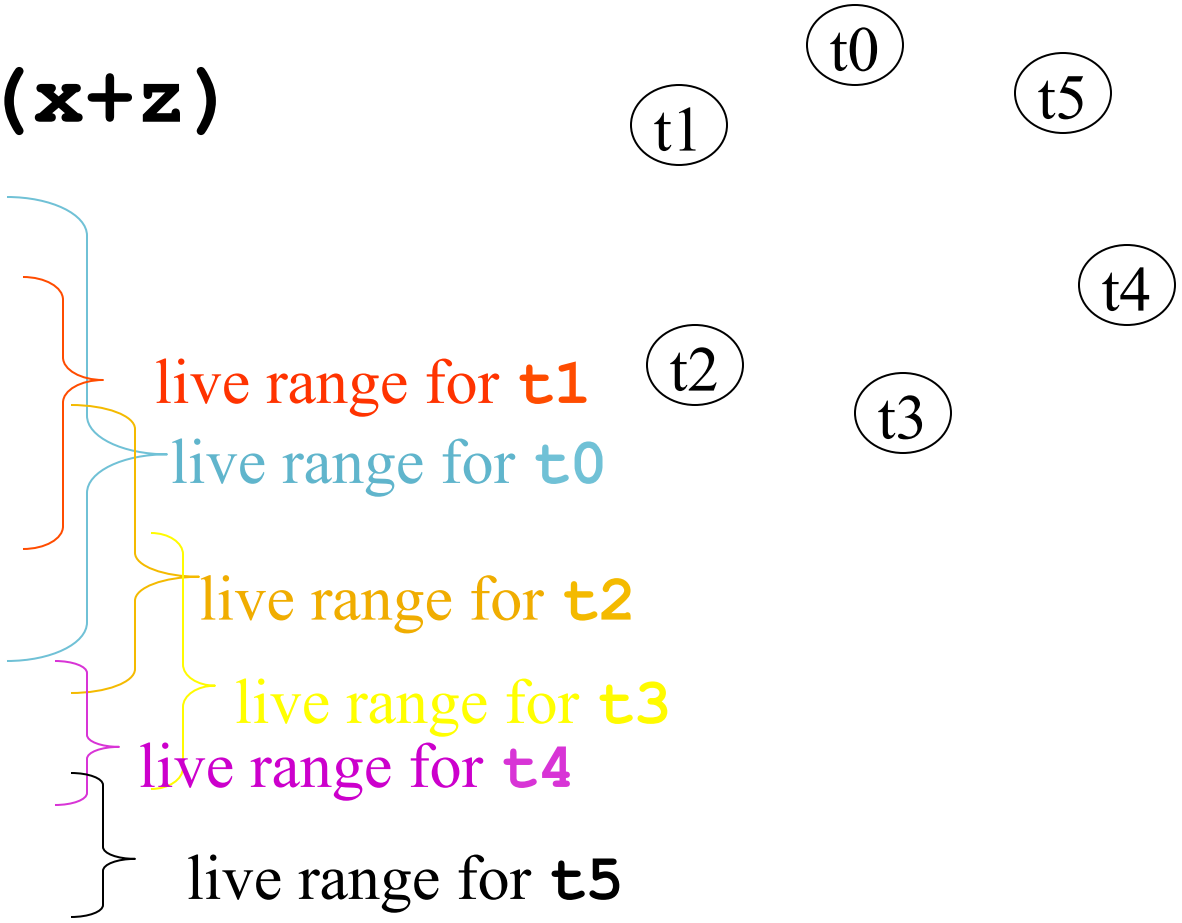
- Temps **`t1`** and **`t2`** *interfere* if there is some program point where they are both live.
- We build a graph where the nodes are temps and the edges represent interference.
- If two temps interfere, then we cannot allocate them to the same register.
- Conversely, if **`t1`** and **`t2`** do not interfere, we can use the same register to hold their values.

Register Coloring

- Assign each node (temp) a register such that if **`t1`** interferes with **`t2`**, then they are given distinct colors.
  - Similar to trying to "color" a map so that adjacent countries have different colors.
  - In general, this problem is NP complete, so we must use heuristics.
- Problem: given *k* registers and *n* > *k* nodes, the graph might not be colorable.
  - Solution: spill a node to the stack.
  - Reconstruct interference graph & try coloring again.
  - Trick: spill temps that are used infrequently and/or have high interference degree.

Example:

```
a := (x+y)*(x+z)

t0 := x
t1 := y
t2 := z
t3 := t0+t1
t4 := t0+t2
t5 := t3*t4
a := t5
```



Graph:

```
a := (x+y)*(x+z)

t0 := x
t1 := y
t2 := z
t3 := t0+t1
t4 := t0+t2
t5 := t3*t4
a := t5
```

live range for **t1**

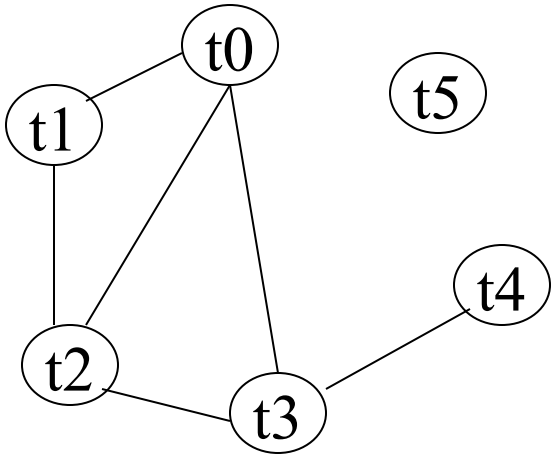
live range for **t0**

live range for **t2**

live range for **t3**

live range for **t4**

live range for **t5**



Coloring:

```
a := (x+y)*(x+z)

t0 := x
t1 := y
t2 := z
t3 := t0+t1
t4 := t0+t2
t5 := t3*t4
a := t5
```

live range for **t1**

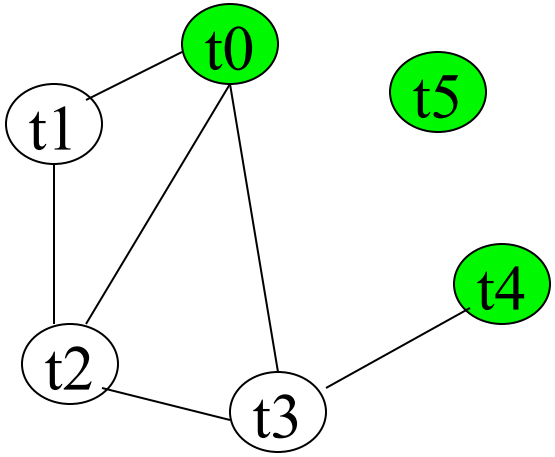
live range for **t0**

live range for **t2**

live range for **t3**

live range for **t4**

live range for **t5**



Coloring:

```
a := (x+y)*(x+z)

t0 := x
t1 := y
t2 := z
t3 := t0+t1
t4 := t0+t2
t5 := t3*t4
a := t5
```

live range for **t1**

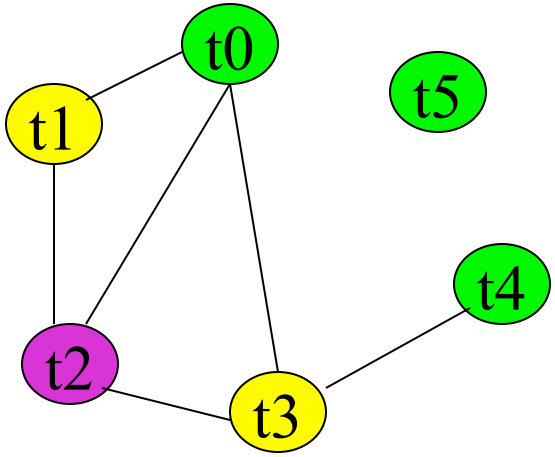
live range for **t0**

live range for **t2**

live range for **t3**

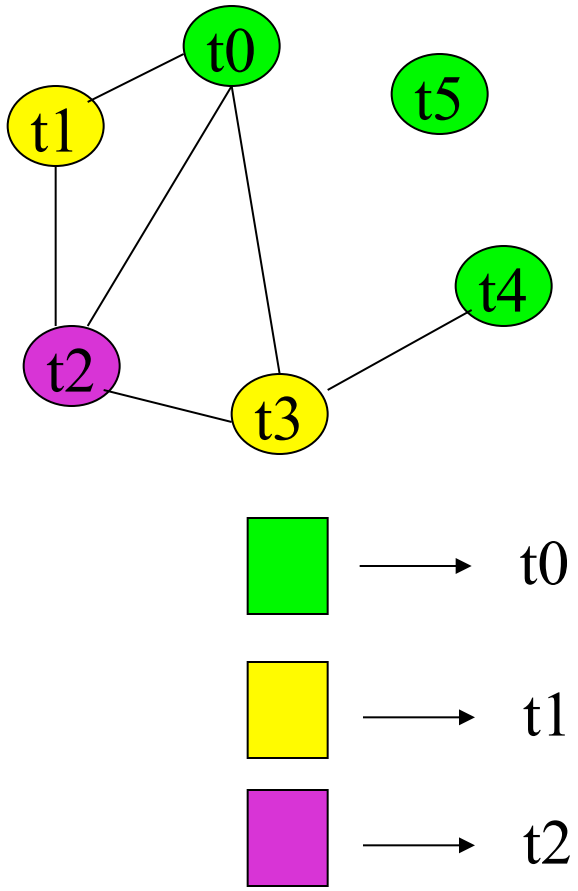
live range for **t4**

live range for **t5**



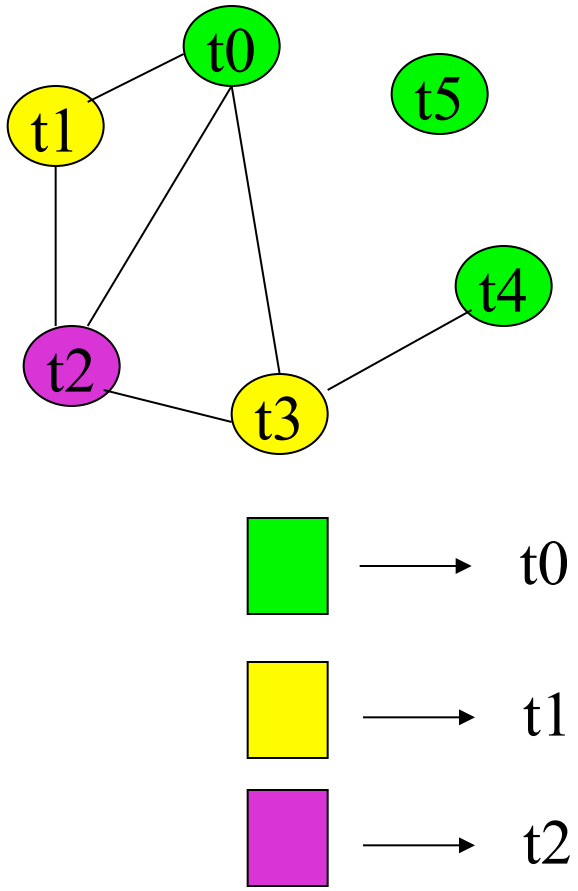
Assignment:

```
a := (x+y)*(x+z)

t0 := x
t1 := y
t2 := z
t3 := t0+t1
t4 := t0+t2
t5 := t3*t4
a := t5
```



Rewrite:

```
a := (x+y)*(x+z)

t0 := x
t1 := y
t2 := z
t3 := t0+t1
t0 := t0+t2
t0 := t3*t0
a := t0
```



Generate Code

```
a := (x+y)*(x+z)

t0 := x       -->  lw $t0,<xoff>($fp)
t1 := y       -->  lw $t1,<yoff>($fp)
t2 := z       -->  lw $t2,<zoff>($fp)
t3 := t0+t1   -->  add $t3,$t0,$t1
t0 := t0+t2    -->  add $t0,$t0,$t2
t0 := t3*t0   -->  mul $t0,$t3,$t2
a := t0       -->  sw $t0,<aoff>($fp)
```