# Topic 7 ½ : Instruction Selection

COS 320

Compiling Techniques

Princeton University
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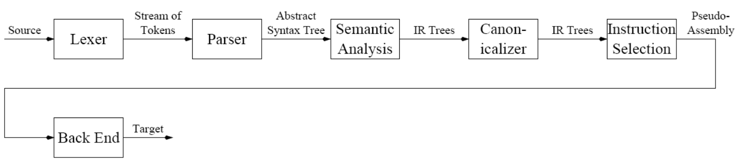
## Instruction Selection




**Instruction Selection**

- Process of finding set of machine instructions that implement operations specified in IR tree.
- Each machine instruction can be specified as an IR tree fragment → *tree pattern*
- Goal of instruction selection is to cover IR tree with non-overlapping tree patterns.

## Our Architecture

- Load/Store architecture
- Relatively large, general purpose register file
  - Data or addresses can reside in registers (unlike Motorola 68000)
  - Each instruction can access any register (unlike x86)
- $r_0$ always contains zero.
- Each instruction has latency of one cycle.
- Execution of only one instruction per cycle.

## Our Architecture

Arithmetic:

| | |
|---|---|
| `ADD` | $r_d = r_{s1} + r_{s2}$ |
| `ADDI` | $r_d = r_s + c$ |
| `SUB` | $r_d = r_{s1} - r_{s2}$ |
| `SUBI` | $r_d = r_s - c$ |
| `MUL` | $r_d = r_{s1} * r_{s2}$ |
| `DIV` | $r_d = r_{s1} / r_{s2}$ |

Memory:

| | |
|---|---|
| `LOAD` | $r_d = M[r_s + c]$ |
| `STORE` | $M[r_{s1} + c] = r_{s2}$ |
| `MOVEM` | $M[r_{s1}] = M[r_{s2}]$ |

## Pseudo-ops

*Pseudo-op* - An assembly operation which does not have a corresponding machine code operation. Pseudo-ops are resolved during assembly.

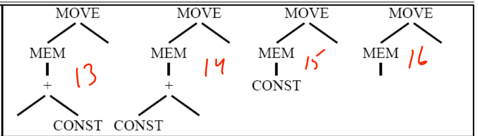
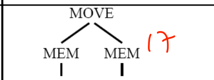
| | | | |
|---|---|---|---|
| `MOV` | $r_d = r_s$ | `ADDI` | $r_d = r_s + 0$ |
| `MOV` | $r_d = r_s$ | `ADD` | $r_d = r_{s1} + r_0$ |
| `MOVI` | $r_d = c$ | `ADDI` | $r_d = r_0 + c$ |

(Pseudo-op can also mean assembly directive, such as `.align`.)

## Instruction Tree Patterns

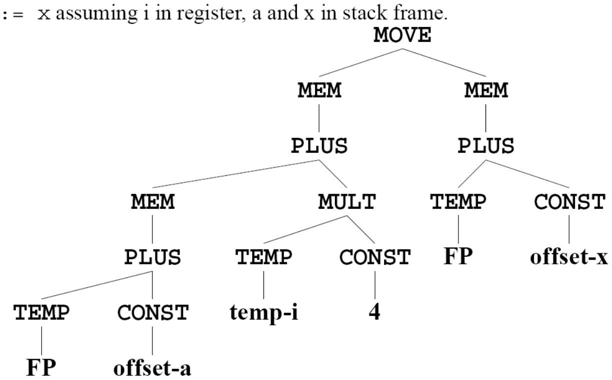
| *Name* | *Effect* | *Trees* |
|---|---|---|
| — | $r_i$ | TEMP 0 |
| ADD | $r_i \quad r_j + r_k$ | + 1 |
| MUL | $r_i \quad r_j \times r_k$ | * 2 |
| SUB | $r_i \quad r_j \quad r_k$ | - 3 |
| DIV | $r_i \quad r_j / r_k$ | / 4 |
| ADDI | $r_i \quad r_j + c$ | + CONST 5; + CONST 6; CONST 7 |
| SUBI | $r_i \quad r_j \quad c$ | - CONST 8 |
| LOAD | $r_i \quad M[r_j + c]$ | MEM + CONST 9; MEM + CONST 10; MEM CONST 11; MEM 12 2 |

## Instruction Tree Patterns

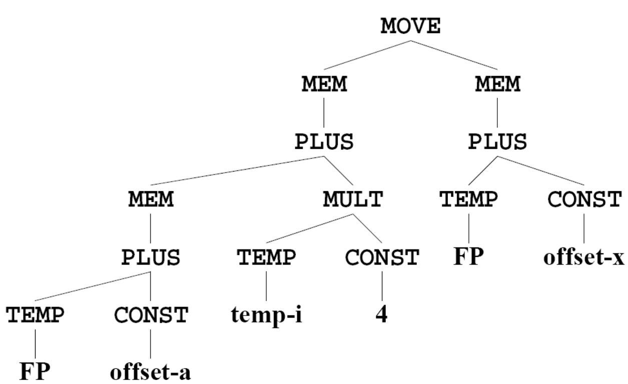
| | | | |
|---|---|---|---|
| STORE | $M[r_j + c]$ | $r_i$ |  |
| MOVEM | $M[r_j]$ | $M[r_i]$ |  |

## Example

`a[i] := x` assuming i in register, a and x in stack frame.




## Individual Node Selection

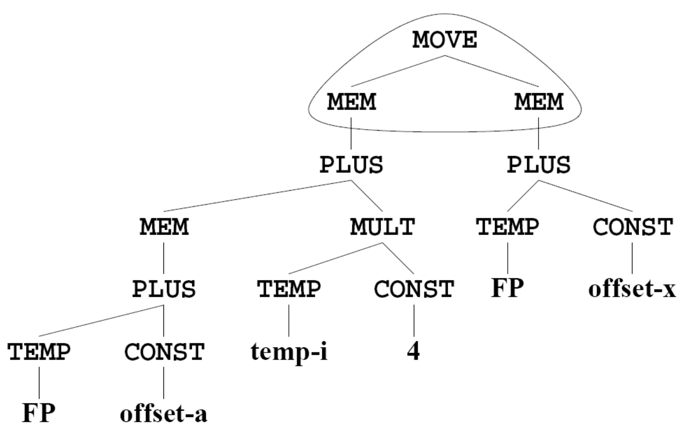


## Individual Node Selection

```
ADDI  r1 = r0 + offset_a
ADD   r2 = r1 + FP
LOAD  r3 = M[r2 + 0]

ADDI  r4 = r0 + 4
MUL   r5 = r4 * r_i

ADD   r6 = r3 + r5

ADDI  r7 = r0 + offset_x
ADD   r8 = r7 + FP
LOAD  r9 = M[r8 + 0]

STORE M[r6 + 0] = r9
```

**9 registers, 10 instructions**

## Random Tiling




## Random Tiling

```
ADDI  r1 = r0 + offset_a
ADD   r2 = r1 + FP
LOAD  r3 = M[r2 + 0]

ADDI  r4 = r0 + 4
MUL   r5 = r4 * r_i

ADD   r6 = r3 + r5

ADDI  r7 = r0 + offset_x
ADD   r8 = r7 + FP
MOVEM M[r6] = M[r8]
```

**Saves a register ($9 \rightarrow 8$) and an instruction ($10 \rightarrow 9$).**

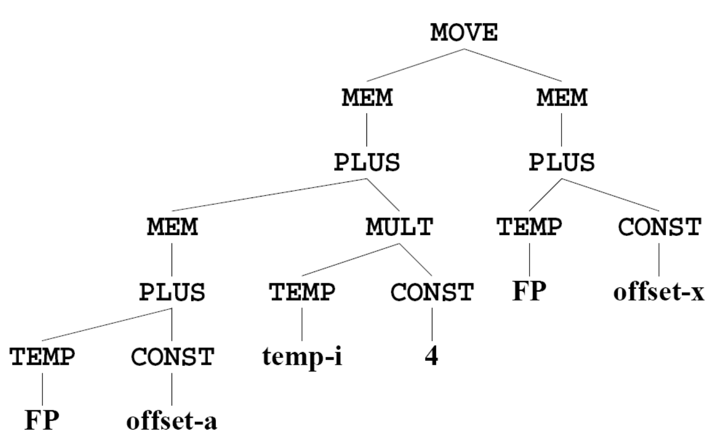
## Node Selection

- There exist many possible tilings - want tiling/covering that results in instruction sequence of *least cost*
  - Sequence of instructions that takes least amount of time to execute.
  - For single issue fixed-latency machine: fewest number of instructions.
- Suppose each instruction has fixed cost:
  - *Optimum Tiling*: tiles sum to lowest possible value - globally "the best"
  - *Optimal Tiling*: no two adjacent tiles can be combined into a single tile of lower cost - locally "the best"
  - Optimal instruction selection easier to implement than Optimum instruction selection.
  - Optimal is roughly equivalent to Optimum for RISC machines.
  - Optimal and Optimum are noticeably different for CISC machines.
- Instructions are not self-contained with individual costs.

## Optimal Instruction Selection: Maximal Munch

- Cover root node of IR tree with largest tile $t$ that fits (most nodes)
  - Tiles of equivalent size ⇒ arbitrarily choose one.
- Repeat for each subtree at leaves of $t$.
- Generate assembly instructions in reverse order - instruction for tile at root emitted last.

## Maximal Munch



## Maximal Munch

```
LOAD  r3 = M[FP + offset_a]

ADDI  r4 = r0 + 4
MUL   r5 = r4 * r_i

ADD   r6 = r3 + r5

ADD   r8 = FP + offset_x
MOVEM M[r6] = M[r8]
```

**5 registers, 6 instructions**

## Maximal Munch

## Assembly Representation

```
structure Assem = struct
  type reg = string
  type temp = Temp.temp
  type label = Temp.label

  datatype instr = OPER of
    {assem: string,
     dst: temp list,
     src: temp list,
     jump: label list option}
  | ...
...
end
```

## Codegen

```
fun codegen(frame)(stm: Tree.stm):Assem.instr list =
let
  val ilist = ref(nil: Assem.instr list)
  fun emit(x) = ilist := x::!ilist
  fun munchStm: Tree.stm -> unit
  fun munchExp: Tree.exp -> Temp.temp
in
  munchStm(stm);
  rev(!ilist)
end
```

## Statement Munch

```
fun munchStm(
  T.MOVE(T.MEM(T.BINOP(T.PLUS, e1, T.CONST(c))), e2)
          ) =
      emit(Assem.OPER{assem="STORE M['s0 + " ^
                            int(c) ^ "] = 's1\n",
                      src=[munchExp(e1), munchExp(e2)],
                      dst=[],
                      jump=NONE})
  | munchStm(T.MOVE(T.MEM(e1), T.MEM(e2))) =
      emit(Assem.OPER{assem="MOVEM M['s0] = M['s1]\n"
                      src=[munchExp(e1), munchExp(e2)],
                      dst=[],
                      jump=NONE})
  | munchStm(T.MOVE(T.MEM(e1), e2)) =
      emit(Assem.OPER{assem="STORE M['s0] = 's1\n"
                      src=[munchExp(e1), munchExp(e2)],
                      dst=[],
                      jump=NONE})
...
```

## Expression Munch

```
and munchExp(T.MEM(T.BINOP(T.PLUS, e1, T.CONST(c)))) =
      let
        val t = Temp.newtemp()
      in
        emit(Assem.OPER{assem="LOAD 'd0 = M['s0 +" ^
                              int(c) ^ "]\n",
                        src=[munchExp(e1)],
                        dst=[t],
                        jump=NONE});
        t
      end
```

## Expression Munch

```
  | munchExp(T.BINOP(T.PLUS, e1, T.CONST(c))) =
      let
        val t = Temp.newtemp()
      in
        emit(Assem.OPER{assem="ADDI 'd0 = 's0 +" ^
                              int(c) ^ "\n",
                        src=[munchExp(e1)],
                        dst=[t],
                        jump=NONE});
        t
      end
...
  | munchExp(T.TEMP(t)) = t
```

## Optimum Instruction Selection

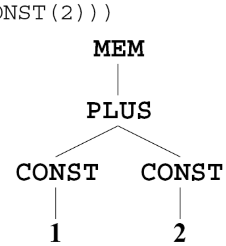
- Find optimum solution for problem (tiling of IR tree) based on optimum solutions for each subproblem (tiling of subtrees)
- Use Dynamic Programming to avoid unnecessary recomputation of subtree costs.
- *cost* assigned to *every* node in IR tree
  - Cost of best instruction sequence that can tile subtree rooted at node.
- Algorithm works bottom-up (Maximum Munch is top-down) - Cost of each subtree $s_j$ ($c_j$) has already been computed.
- For each tile $t$ of cost $c$ that matches at node $n$, cost of matching $t$ is:

$$c_t + \sum_{\text{all leaves } i \text{ of } t} c_i$$

- Tile is chosen which has minimum cost.

## Optimum Instruction Selection – Example

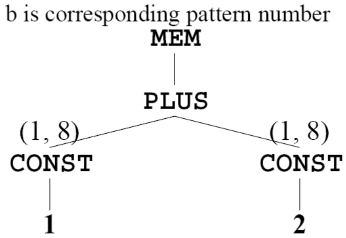
```
MEM(BINOP(PLUS, CONST(1), CONST(2))))

MEM(PLUS(CONST(1), CONST(2)))
```



## Optimum Instruction Selection – Example

**Step 1: Find cost of root node**

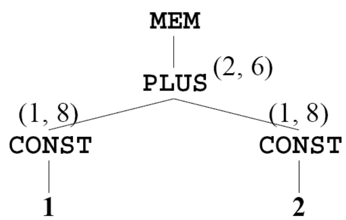
(a,b): a is minimum cost, b is corresponding pattern number




Consider PLUS node:

| Pattern | Cost | Leaves Cost | Total |
|---|---|---|---|
| (2) PLUS(e1, e2) | 1 | 2 | 3 |
| (6) PLUS(CONST(c), e1) | 1 | 1 | 2 |
| (7) PLUS(e1, CONST(c)) | 1 | 1 | 2 |

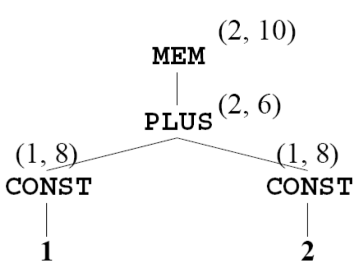
## Optimum Instruction Selection – Example




Consider MEM node:

| Pattern | Cost | Leaves Cost | Total |
|---|---|---|---|
| (13) MEM(e1) | 1 | 2 | 3 |
| (10) MEM(PLUS(e1, CONST(c)) | 1 | 1 | 2 |
| (11) MEM(PLUS(CONST(c), e1) | 1 | 1 | 2 |

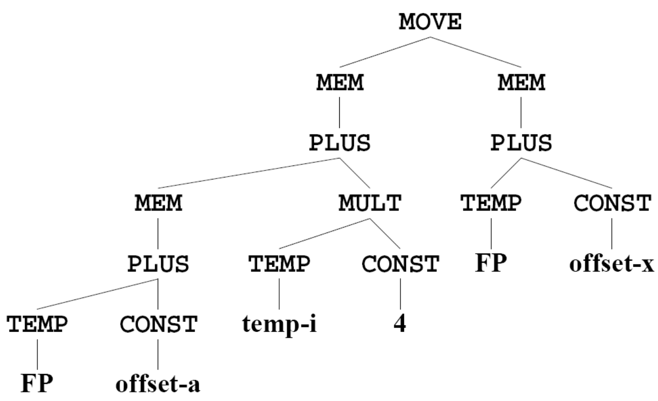
## Optimum Insruction Selection – Example



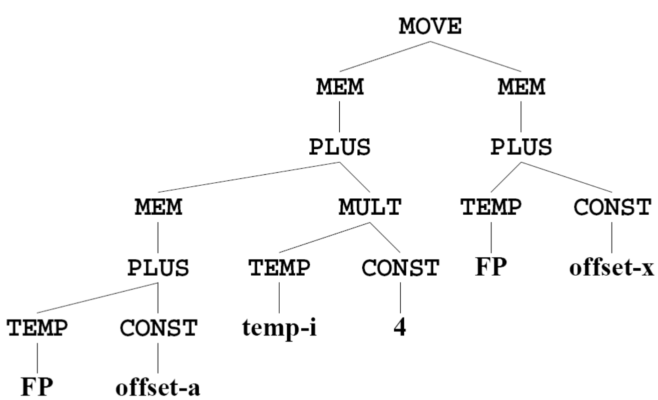

**Step 2: Emit instructions**

```
ADDI r1 = r0 + 1
LOAD r2 = M[r1 + 2]
```

## Optimum Instruction Selection – Big Example




## Optimum Instruction Selection – Big Example




## Optimum Instruction Selection – Big Example

```
LOAD  r3 = M[FP + offset_a]

ADDI  r4 = r0 + 4
MUL   r5 = r4 * r_i

ADD   r6 = r3 + r5

LOAD  r9 = M[FP + offset_x]
STORE M[r6] = r9
```

**5 registers, 6 instructions**

Optimal tree generated by Maximum Munch is also optimum...