

# Compiler Construction 2009/2010

## Instruction Selection

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# Optimal vs Optimum Tiling

## Optimal Tiling

No two adjacent tiles can be replaced by a larger tile of lower cost.

## Optimum Tiling

The total cost of the tiling is minimal among all possible tilings.

- Tiling is optimum  $\Rightarrow$  tiling is optimal

# Implementation of Optimal Tiling

## Maximal Munch Algorithm (Top Down)

```
Temp munchExpr (Tree.Exp e) {
  test patterns from largest to smallest

  choose the first matching pattern
    with instruction INS

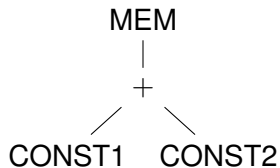
  foreach (e_i : wildcard (pattern, e))
    recursively invoke temp_i = munchExpr (e_i)

  emit INS using temp_i as arguments
    putting result into new temp_0

  return temp_0
}
```

# Optimum Tiling

## Example



pattern	instr	tile cost	wildcard cost	total cost
CONST	ADDI	1	0	1

# Optimum Tiling

Example (cont'd)

pattern	instr	tile cost	wildcard cost	total cost
	ADD	1	1+1	3
	ADDI	1	1	2
	ADDI	1	1	2

# Optimum Tiling

Example (cont'd)

pattern	instr	tile cost	wildcard cost	total cost
MEM	LOAD	1	2	3
MEM   +				
CONST	LOAD	1	1	2
MEM   +				
CONST	ADDI	1	1	2

```
graph TD; MEM1[MEM] --- MEM2[MEM]; MEM2 --- P1[+]; P1 --- W1[ ]; P1 --- CONST1[CONST]; CONST1 --- MEM3[MEM]; MEM3 --- P2[+]; P2 --- CONST2[CONST]; P2 --- W2[ ]
```

# Optimum Tiling

## Emitted Code

```
ADDI  r1 ← r0 + 1  
LOAD  r1 ← M[r1 + 2]
```

# Implementation of Optimum Tiling

## Dynamic Programming (Bottom Up)

```
void matchExpr (Tree.Exp e) {
    for (Tree.Exp kid : e.kids())
        matchExpr (kid);

    cost = INFINITY
    for each pattern P_i
        if (P_i.matches (e)) {
            cost_i = cost (P_i)
                + sum ((wildcard (P_i, e)).mincost)
            if (cost_i < cost) { cost = cost_i; choice =
        }
    e.matched = P_{choice}
    e.mincost = cost
}
```



# Implementation of Optimum Tiling

## Collecting the Match (Top Down)

```
Temp emission (Tree.Exp e) {  
  foreach (e_i : wildcard (e.matched, e)) {  
    temp_i = emission (e_i)  
  }  
  
  emit INS using temp_i as arguments  
    putting result into new temp_0  
  
  return temp_0  
}
```

# Implementation of Pattern Matching

- Additional side conditions (e.g., size of constants, special constants)
  - Matching of patterns can be done with a decision tree that avoids checking the same node twice
  - The bottom up matcher can remember partial matches and avoid rechecking the same nodes
- ⇒ tree automata

# Tree Automata

A bottom-up tree automaton is  $\mathcal{M} = (Q, \Sigma, \delta, F)$  where

- $Q$  is a finite set of states
- $\Sigma$  a ranked alphabet (the tree constructors)
- $\delta \subseteq \Sigma^{(n)} \times Q^n \times Q$  ( $\forall n$ ) the transition relation
- $F \subseteq Q$  the set of final states

$\mathcal{M}$  is deterministic if  $\delta$  is a function.

Define  $\Rightarrow$  on  $T_{\Sigma+Q}$  by

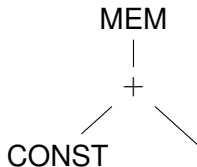
$$t[F(q_1, \dots, q_n)] \Rightarrow t[q_0] \quad \text{if} \quad (F, q_1, \dots, q_n, q_0) \in \delta$$

$t \in L(\mathcal{M})$  if  $t \Rightarrow^* q$  with  $q \in F$

# Tree Automata

## Example

Tree automaton for



- $Q = \{q_t, q_c, q_a, q_m\}$

- $F = \{q_m\}$

- $\delta =$

$\Sigma$	$q_1$	$q_2$	$q_{out}$
CONST			$q_c$
TEMP			$q_t$
+	$q_c$	$q_t$	$q_a$
MEM	$q_a$		$q_m$

# Optimum Tiling with Tree Automata

- Generate a bu tree automaton for each pattern
- Simulate them in parallel on expression tree
- At each node
  - determine all patterns whose root matches the current node
  - compute their cost and mark the node with the minimum cost pattern
- There are tools to compile a pattern specification to such an automaton  $\Rightarrow$  BURG (Fraser, Hanson, Proebsting)

# Tree Grammars

- Extension: Different pattern sets leading to different kinds of results
  - Some architectures have different kinds of registers that obey different restrictions
  - Set of patterns for each kind of register
  - Example: M680x0 distinguishes data and address registers, only the latter may serve for address calculations and indirect addressing
- ⇒ Tree grammar needed

# Tree Grammars

## Definition

A context-free tree grammar is defined by  $\mathcal{G} = (N, \Sigma, P, S)$  where

- $N$  is a finite set of non-terminals
- $\Sigma$  is a ranked alphabet
- $S \in N$  is the start symbol
- $P \subseteq N \times T_{\Sigma+N}$

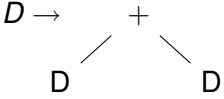
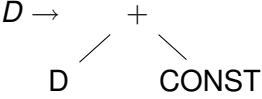
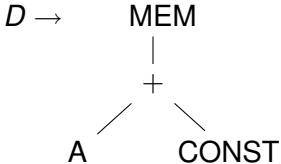
Define  $\Rightarrow$  on  $T_{\Sigma+N}$  by

$$t[A] \Rightarrow t[r] \quad \text{in} \quad A \rightarrow r \in P$$

$t \in L(\mathcal{G})$  if  $S \Rightarrow^* t \in T_{\Sigma}$

# Tree Grammars

Example: The Schizo-Jouette Architecture (Excerpt)

Instruction	Effect	Pattern
ADD	$d_i \leftarrow d_j + d_k$	$D \rightarrow$ 
ADDI	$d_i \leftarrow d_j + c$	$D \rightarrow$ 
MOVEA	$d_i \leftarrow a_j$	$D \rightarrow A$
MOVED	$a_i \leftarrow d_j$	$A \rightarrow D$
LOAD	$d_i \leftarrow M[a_j + c]$	$D \rightarrow$ MEM 



# Efficiency of Tiling

- $N$  number of nodes in input tree
  - $T$  number of patterns
  - $K$  average number of labeled nodes in pattern
  - $K'$  maximum number of nodes to check for a match
  - $T'$  average number of patterns that match at each node
  - **Maximal munch.** Each match consumes  $K$  nodes: test for matches at  $N/K$  nodes. At each candidate node, choose pattern with  $K' + T'$  tests.  
 $(K' + T')N/K$  steps on average. Worst case:  $K = 1$ .
  - **Dynamic programming.** Tests every pattern at every node:  $(K' + T')N$ .
- ⇒ same linear worst-case complexity.  $(K' + T')/K$  is constant, anyway.

# CISC vs RISC

## Challenges for Instruction Selection and Register Allocation

RISC	CISC
32 registers	few registers (16, 8, 6)
one class of registers	different classes with restricted operations
ALU instructions only between registers	ALU operations with memory operands
three-address instructions	two-address instructions
$r_1 \leftarrow r_2 \oplus r_3$	$r_1 \leftarrow r_1 \oplus r_2$
one addressing mode for load/store	several addressing modes
every instruction 32 bits long	different instruction lengths
one result / instruction	instructions w/ side effects

## Pentium / x86 (32-bit)

- six GPR, *sp*, *bp*
- multiply / divide only on *eax*
- generally two-address instructions

## MC 680x0 (32-bit)

- 8 data registers, 7 address registers, 2 stack registers
- ALU operations generally on data registers, indirect addressing only through address registers
- generally two-address instructions
- esoteric addressing modes (68030)

# Challenges

- **[Few Registers]** generate temporaries and rely on register allocation
- **[Restricted Registers]** generate extra moves and hope that register allocation can get rid of them. Example:
  - Multiply on Pentium requires one operand and destination in `eax`
  - Most-significant word of result stored to `edx`

Hence for  $t_1 \leftarrow t_2 \cdot t_3$  generate

```
mov  eax, t2      eax ← t2
mul  t3           eax ← eax · t3; edx ← garbage
mov  t1,  eax     t3 ← eax
```

# Challenges II

- **[Two-address instructions]**

Generate extra move instructions.

For  $t_1 \leftarrow t_2 + t_3$  generate

```
mov  t1, t2    t1 ← t2
add  t1, t3    t1 ← t1 + t3;
```

- **[Special addressing modes]**

Example: memory addressing

```
mov  eax, [ebp-8]
add  eax, ecx          add [ebp-8], ecx
mov  [ebp-8], eax
```

Two choices:

- 1 Ignore and use separate load and store instructions. Same speed, but an extra register gets trashed.
- 2 Avoid register pressure and use addressing mode. More work for the pattern matcher.

# Challenges III

- **[Variable-length instructions]**  
No problem for instruction selection or register allocation.  
Assembler deals with it.
- **[Instructions with side effects]**  
Example: autoincrement after memory fetch (MC 680x0)

$$r_2 \leftarrow M[r_1]; \quad r_1 \leftarrow r_1 + 4$$

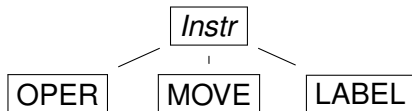
Hard to incorporate in tree-pattern based instruction selection.

- 1 Ignore...
- 2 Ad-hoc solution
- 3 Different algorithm for instruction selection

# Abstract Assembly Language

## Output of Instruction Selection

Class hierarchy for representing instructions



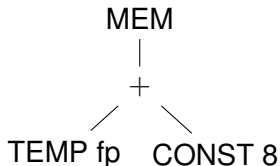
Each instruction specifies a

- set of defined temporaries
- set of used temporaries
- set of branch targets

each of which may be empty

# Abstract Assembly Language

## Creating an Operation



```
new OPER ("LOAD 'd0 <- M['s0+8]",  
          L (new Temp(), null), // targets: defined  
          L (frame.FP, null)); // sources: used
```

- Independent of register allocation and jump labels



# Abstract Assembly Language

## Important

An operation's def and use set must account for all defined and used registers.

- Example: the multiplication instruction on Pentium

```
new OPER ("mul 's0",  
          L (pentium.EAX, L (pentium.EDX, null))  
          L (argTemp, L (pentium.EAX, null)));
```

- Example: a procedure call trashes many registers (see the calling convention of the architecture)
  - return address
  - return-value register
  - caller-save registers