Compiler Optimisation

Instruction Selection

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Introduction

This lecture:

- Naive translation and ILOC
- Cost based instruction selection
- Bottom up tiling on low level AST
- Alternative approach based on peephole optimisation
- Super-optimisation
- Multimedia code generation

Code generation

- Aim to generate the most efficient assembly code
- Decouple problem into three phases:
  - Instruction selection
  - Instruction scheduling
  - Register allocation
- In general phases NP-complete and strongly interact
- In practise good solutions can be found
- Instruction scheduling : would like to automate wherever possible – re-targetable ISA specific translation rules plus generic optimiser

ILOC

Instruction set review

Typical ILOC instructions (📖EaC Appendix A)

`load`	r_1	$\Rightarrow r_2$	$r_2 = \text{Mem}[\ r_1\ ]$
`loadI`	c_1	$\Rightarrow r_1$	$r_1 = c_1$
`loadAI`	$r_1,\ c_1$	$\Rightarrow r_2$	$r_2 = \text{Mem}[\ r_1 + c_1\ ]$
`loadAO`	$r_1,\ r_2$	$\Rightarrow r_3$	$r_3 = \text{Mem}[\ r_1 + r_2\ ]$
`store`	r_1	$\Rightarrow r_2$	$\text{Mem}[\ r_2\ ] = r_1$
`storeAI`	r_1	$\Rightarrow r_2,\ c_1$	$\text{Mem}[\ r_2 + c_1\ ] = r_1$
`storeAO`	r_1	$\Rightarrow r_2,\ r_3$	$\text{Mem}[\ r_2 + r_3\ ] = r_1$
`i2i`	r_1	$\Rightarrow r_2$	$r_2 = r_1$
`add`	$r_1,\ r_2$	$\Rightarrow r_3$	$r_3 = r_1 + r_2$
`addI`	$r_1,\ c_1$	$\Rightarrow r_2$	$r_2 = r_1 + c_1$
	Similar for arithmetic, logical, and shifts		
`jump`		r_1	$\text{PC} = r_1$
`jumpI`		l_1	$\text{PC} = l_1$
`cbr`	r_1	$\Rightarrow l_1,\ l_2$	$\text{PC} = r_1\ ?\ l_1 : l_2$

ILOC

- Many ways to do the same thing
- If operators assigned to distinct functional units - big impact

Different ways to move register, $r_i \Rightarrow r_j$

`i2i`	r_i	$\Rightarrow r_j$
`addI`	$r_i, 0$	$\Rightarrow r_j$
`subI`	$r_i, 0$	$\Rightarrow r_j$
`multI`	$r_i, 1$	$\Rightarrow r_j$
`divI`	$r_i, 1$	$\Rightarrow r_j$
`lshiftI`	$r_i, 0$	$\Rightarrow r_j$
`rshiftI`	$r_i, 0$	$\Rightarrow r_j$
`and`	r_i, r_i	$\Rightarrow r_j$
`orI`	$r_i, 0$	$\Rightarrow r_j$
`xorI`	$r_i, 0$	$\Rightarrow r_j$

ILOC
Naïve selection

- Simple walk through of first lecture generates inefficient code
- Takes a naive view of location of data and does not exploit different addressing modes available

Different code to compute `g * h`

Assume `g` and `h` in global spaces `G` and `H`, both at offset 4

```
 loadI   @G      ⇒ r5
 loadI   4       ⇒ r6
loadAO   r5, r6  ⇒ r7
 loadI   @H      ⇒ r8
 loadI   4       ⇒ r9
loadAO   r8, r9  ⇒ r10
  mult   r7, r10 ⇒ r11
```

```
 loadI   4       ⇒ r5
loadAI   r5,@G   ⇒ r6
loadAI   r5,@H   ⇒ r7
  mult   r6, r7  ⇒ r8
```

Instruction selection via tree pattern matching

- IR is in low level AST form exposing storage type of operands
- Tile AST with operation trees generating $< ast, op >$ i.e. *op* could implement abstract syntax tree *ast*
- Recursively tile tree and bottom-up select the cheapest tiling - locally optimal.
- Overlaps of trees must match
  - destination of one tree is the source of another
  - must agree on storage location and type - register or memory, int or float, etc
- Operations are connected to AST subtrees by a set of *ambiguous* rewrite rules
- Rules have costs - ambiguity allows cost based choice

Instruction selection via tree pattern matching

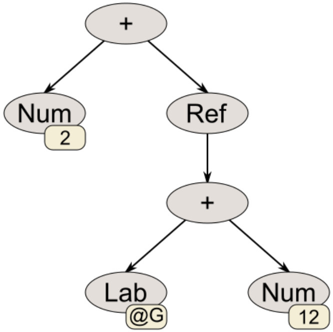
Rewrite rules

Subset of rules

Id	**Production**	**Code Template**	
1:	$Reg \rightarrow Lab$	`loadI`	$lbl \Rightarrow r_{new}$
2:	$Reg \rightarrow Num$	`loadI`	$n_1 \Rightarrow r_{new}$
3:	$Reg \rightarrow Ref(Reg)$	`load`	$r_1 \Rightarrow r_{new}$
4:	$Reg \rightarrow Ref(+(Reg_1, Reg_2))$	`loadAO`	$r_1, r_2 \Rightarrow r_{new}$
5:	$Reg \rightarrow Ref(+(Reg, Num))$	`loadAI`	$r_1, n_1 \Rightarrow r_{new}$
6:	$Reg \rightarrow +(Reg_1, Reg_2))$	`add`	$r_1, r_2 \Rightarrow r_{new}$
7:	$Reg \rightarrow +(Reg, Num))$	`addI`	$r_1, n_1 \Rightarrow r_{new}$
8:	$Reg \rightarrow +(Num, Reg))$	`addI`	$r_1, n_1 \Rightarrow r_{new}$

Instruction selection via tree pattern matching

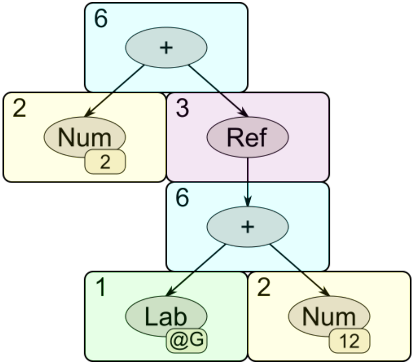
Rewrite rules



Begin tiling the AST bottom up

Instruction selection via tree pattern matching

Rewrite rules



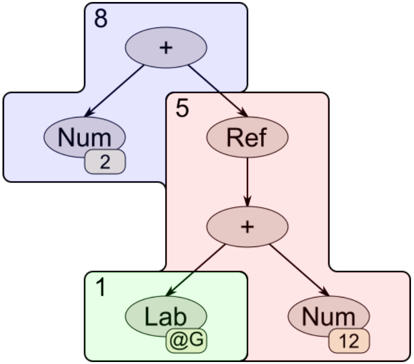
Code produced

`loadI`	`@`G	$\Rightarrow r_1$
`loadI`	12	$\Rightarrow r_2$
`add`	r_1, r_2	$\Rightarrow r_3$
`load`	r_3	$\Rightarrow r_4$
`loadI`	2	$\Rightarrow r_5$
`add`	r_4, r_5	$\Rightarrow r_6$

Bad tiling: productions used

1:	$Reg \rightarrow Lab$	`loadI` $lbl \Rightarrow r_{new}$
2:	$Reg \rightarrow Num$	`loadI` $n_1 \Rightarrow r_{new}$
3:	$Reg \rightarrow Ref(Reg)$	`load` $r_1 \Rightarrow r_{new}$
6:	$Reg \rightarrow +(Reg_1, Reg_2))$	`add` $r_1, r_2 \Rightarrow r_{new}$

Instruction selection via tree pattern matching
Rewrite rules



- Many different sequences available
- Selecting lowest cost bottom-up gives

Code produced

`loadI`	$@G$	$\Rightarrow r_1$
`loadAI`	$r_1, 12$	$\Rightarrow r_2$
`addI`	$r_2, 2$	$\Rightarrow r_3$

Good tiling: productions used

1: $Reg \rightarrow Lab$	`loadI` $lbl \Rightarrow r_{new}$
5: $Reg \rightarrow Ref(+(Reg, Num))$	`loadAI` $r_1, n_1 \Rightarrow r_{new}$
8: $Reg \rightarrow +(Num, Reg))$	`addI` $r_1, n_1 \Rightarrow r_{new}$

Instruction selection via tree pattern matching

Cost based selection

- Examples assume all operations are equal cost
- Certain ops may be more expensive - divs
- Cost of bottom matching can be reduced using table lookups

Peephole selection

- Other approaches available - peephole optimisation
  - Expand code into operations below machine level
  - Simplify by rules over sliding window
  - Match against machine instructions

Peephole instruction selection

Selection for: $b - 2 * c$

$$
\begin{array}{lcl}
r_{10} & \leftarrow & 2 \\
r_{11} & \leftarrow & \texttt{@G} \\
r_{12} & \leftarrow & 12 \\
r_{13} & \leftarrow & r_{11} + r_{12} \\
r_{14} & \leftarrow & M(r_{13}) \\
r_{15} & \leftarrow & r_{10} \times r_{14} \\
r_{16} & \leftarrow & -16 \\
r_{17} & \leftarrow & r_{arp} + r_{16} \\
r_{18} & \leftarrow & M(r_{17}) \\
r_{19} & \leftarrow & M(r_{18}) \\
r_{20} & \leftarrow & r_{19} - r_{15} \\
r_{21} & \leftarrow & 4 \\
r_{22} & \leftarrow & r_{arp} + r_{21} \\
M(r_{22}) & \leftarrow & r_{20}
\end{array}
$$

Elaborate into very low-level code

Peephole instruction selection

Selection for: $b - 2 * c$

r_{10}	$\leftarrow$	2
r_{11}	$\leftarrow$	`@G`
r_{12}	$\leftarrow$	12
r_{13}	$\leftarrow$	$r_{11} + r_{12}$
r_{14}	$\leftarrow$	$M(r_{13})$
r_{15}	$\leftarrow$	$r_{10} \times r_{14}$
r_{16}	$\leftarrow$	-16
r_{17}	$\leftarrow$	$r_{arp} + r_{16}$
r_{18}	$\leftarrow$	$M(r_{17})$
r_{19}	$\leftarrow$	$M(r_{18})$
r_{20}	$\leftarrow$	$r_{19} - r_{15}$
r_{21}	$\leftarrow$	4
r_{22}	$\leftarrow$	$r_{arp} + r_{21}$
$M(r_{22})$	$\leftarrow$	r_{20}

First window, no simplification available; advance window

Peephole instruction selection

Selection for: $b - 2 * c$

$$\begin{array}{lcl}
r_{10} & \leftarrow & 2 \\
\hline
r_{11} & \leftarrow & \texttt{@G} \\
r_{12} & \leftarrow & 12 \\
r_{13} & \leftarrow & r_{11} + r_{12} \\
\hline
r_{14} & \leftarrow & M(r_{13}) \\
r_{15} & \leftarrow & r_{10} \times r_{14} \\
r_{16} & \leftarrow & -16 \\
r_{17} & \leftarrow & r_{arp} + r_{16} \\
r_{18} & \leftarrow & M(r_{17}) \\
r_{19} & \leftarrow & M(r_{18}) \\
r_{20} & \leftarrow & r_{19} - r_{15} \\
r_{21} & \leftarrow & 4 \\
r_{22} & \leftarrow & r_{arp} + r_{21} \\
M(r_{22}) & \leftarrow & r_{20}
\end{array}$$

Substitute r_{12} into r_{13}; r_{12} dead so remove

Peephole instruction selection

Selection for: $b - 2 * c$

$$
\begin{array}{lcl}
r_{10} & \leftarrow & 2 \\
\hline
r_{11} & \leftarrow & \texttt{@G} \\
r_{13} & \leftarrow & r_{11} + 12 \\
r_{14} & \leftarrow & M(r_{13}) \\
\hline
r_{15} & \leftarrow & r_{10} \times r_{14} \\
r_{16} & \leftarrow & -16 \\
r_{17} & \leftarrow & r_{arp} + r_{16} \\
r_{18} & \leftarrow & M(r_{17}) \\
r_{19} & \leftarrow & M(r_{18}) \\
r_{20} & \leftarrow & r_{19} - r_{15} \\
r_{21} & \leftarrow & 4 \\
r_{22} & \leftarrow & r_{arp} + r_{21} \\
M(r_{22}) & \leftarrow & r_{20}
\end{array}
$$

Substitute r_{13} into r_{14}; r_{13} dead so remove

Peephole instruction selection

Selection for: $b - 2 * c$

$$\begin{array}{lcl}
r_{10} & \leftarrow & 2 \\
\hline
r_{11} & \leftarrow & \text{@G} \\
r_{14} & \leftarrow & M(r_{11} + 12) \\
r_{15} & \leftarrow & r_{10} \times r_{14} \\
\hline
r_{16} & \leftarrow & -16 \\
r_{17} & \leftarrow & r_{arp} + r_{16} \\
r_{18} & \leftarrow & M(r_{17}) \\
r_{19} & \leftarrow & M(r_{18}) \\
r_{20} & \leftarrow & r_{19} - r_{15} \\
r_{21} & \leftarrow & 4 \\
r_{22} & \leftarrow & r_{arp} + r_{21} \\
M(r_{22}) & \leftarrow & r_{20}
\end{array}$$

No simplification available; advance window

Peephole instruction selection

Selection for: $b - 2 * c$

$$\begin{array}{lcl}
r_{10} & \leftarrow & 2 \\
r_{11} & \leftarrow & \texttt{@G} \\
\hline
r_{14} & \leftarrow & M(r_{11} + 12) \\
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Peephole instruction selection

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r_{17} & \leftarrow & r_{arp} + r_{16} \\
\hline
r_{18} & \leftarrow & M(r_{17}) \\
r_{19} & \leftarrow & M(r_{18}) \\
r_{20} & \leftarrow & r_{19} - r_{15} \\
r_{21} & \leftarrow & 4 \\
r_{22} & \leftarrow & r_{arp} + r_{21} \\
M(r_{22}) & \leftarrow & r_{20}
\end{array}$$

Substitute r_{16} into r_{17}; r_{16} dead so remove

Peephole instruction selection

Selection for: $b - 2 * c$

$$
\begin{array}{lcl}
r_{10} & \leftarrow & 2 \\
r_{11} & \leftarrow & @G \\
r_{14} & \leftarrow & M(r_{11} + 12) \\
\hline
r_{15} & \leftarrow & r_{10} \times r_{14} \\
r_{17} & \leftarrow & r_{arp} - 16 \\
r_{18} & \leftarrow & M(r_{17}) \\
\hline
r_{19} & \leftarrow & M(r_{18}) \\
r_{20} & \leftarrow & r_{19} - r_{15} \\
r_{21} & \leftarrow & 4 \\
r_{22} & \leftarrow & r_{arp} + r_{21} \\
M(r_{22}) & \leftarrow & r_{20}
\end{array}
$$

Substitute r_{17} into r_{18}; r_{17} dead so remove

Peephole instruction selection

Selection for: $b - 2 * c$

$$
\begin{array}{lcl}
r_{10} & \leftarrow & 2 \\
r_{11} & \leftarrow & @G \\
r_{14} & \leftarrow & M(r_{11} + 12) \\
\hline
r_{15} & \leftarrow & r_{10} \times r_{14} \\
r_{18} & \leftarrow & M(r_{arp} - 16) \\
r_{19} & \leftarrow & M(r_{18}) \\
\hline
r_{20} & \leftarrow & r_{19} - r_{15} \\
r_{21} & \leftarrow & 4 \\
r_{22} & \leftarrow & r_{arp} + r_{21} \\
M(r_{22}) & \leftarrow & r_{20}
\end{array}
$$

No simplification available; advance window

Peephole instruction selection

Selection for: $b - 2 * c$

$$\begin{array}{lcl}
r_{10} & \leftarrow & 2 \\
r_{11} & \leftarrow & @\mathrm{G} \\
r_{14} & \leftarrow & M(r_{11} + 12) \\
r_{15} & \leftarrow & r_{10} \times r_{14} \\
\hline
r_{18} & \leftarrow & M(r_{arp} - 16) \\
r_{19} & \leftarrow & M(r_{18}) \\
r_{20} & \leftarrow & r_{19} - r_{15} \\
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r_{21} & \leftarrow & 4 \\
r_{22} & \leftarrow & r_{arp} + r_{21} \\
M(r_{22}) & \leftarrow & r_{20}
\end{array}$$

No simplification available; advance window

Peephole instruction selection

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No simplification available; advance window

Peephole instruction selection

Selection for: $b - 2 * c$

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r_{10} & \leftarrow & 2 \\
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r_{21} & \leftarrow & 4 \\
r_{22} & \leftarrow & r_{arp} + r_{21} \\
\hline
M(r_{22}) & \leftarrow & r_{20}
\end{array}$$

Substitute r_{21} into r_{22}; r_{21} dead so remove

Peephole instruction selection

Selection for: $b - 2 * c$

r_{10}	$\leftarrow$	2
r_{11}	$\leftarrow$	@G
r_{14}	$\leftarrow$	$M(r_{11} + 12)$
r_{15}	$\leftarrow$	$r_{10} \times r_{14}$
r_{18}	$\leftarrow$	$M(r_{arp} - 16)$
r_{19}	$\leftarrow$	$M(r_{18})$
r_{20}	$\leftarrow$	$r_{19} - r_{15}$
r_{22}	$\leftarrow$	$r_{arp} + 4$
$M(r_{22})$	$\leftarrow$	r_{20}

Substitute r_{22} into $M(r_{22})$; r_{22} dead so remove

Peephole instruction selection

Selection for: $b - 2 * c$

$$\begin{array}{lcl}
r_{10} & \leftarrow & 2 \\
r_{11} & \leftarrow & @G \\
r_{14} & \leftarrow & M(r_{11} + 12) \\
r_{15} & \leftarrow & r_{10} \times r_{14} \\
r_{18} & \leftarrow & M(r_{arp} - 16) \\
r_{19} & \leftarrow & M(r_{18}) \\
\hline
r_{20} & \leftarrow & r_{19} - r_{15} \\
M(r_{arp} + 4) & \leftarrow & r_{20} \\
\hline
\end{array}$$

No more code to bring into window

Peephole instruction selection

Selection for: $b - 2 * c$

$$
\begin{array}{lcl}
r_{10} & \leftarrow & 2 \\
r_{11} & \leftarrow & @G \\
r_{14} & \leftarrow & M(r_{11} + 12) \\
r_{15} & \leftarrow & r_{10} \times r_{14} \\
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r_{19} & \leftarrow & M(r_{18}) \\
r_{20} & \leftarrow & r_{19} - r_{15} \\
M(r_{arp} + 4) & \leftarrow & r_{20}
\end{array}
$$

Simplified code is 8 instructions versus 14

Peephole instruction selection

Selection for: $b - 2 * c$

loadI	2	$\Rightarrow$	r_{10}
loadI	@G	$\Rightarrow$	r_{11}
loadAI	$r_{11} + 12$	$\Rightarrow$	r_{14}
mult	r_{10}, r_{14}	$\Rightarrow$	r_{15}
loadAI	$r_{arp}, -16$	$\Rightarrow$	r_{18}
load	r_{18}	$\Rightarrow$	r_{19}
sub	r_{19}, r_{15}	$\Rightarrow$	r_{20}
storeAI	r_{20}	$\Rightarrow$	$r_{arp}, 4$

Match against machine instructions

Peephole selection

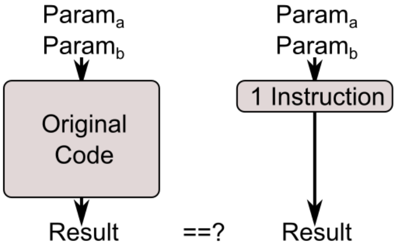
- Works well with linear IR and gives in practise similar performance
- Sensitive to window size - difficult to argue for optimality
- Needs knowledge of when values are dead
- Has difficulty handling general control-flow

Super-optimisation

- Super-optimisers *search* for the best instruction sequence
- Generally very slow - minutes, hours, or weeks!
- Only suitable for very small, hot kernels

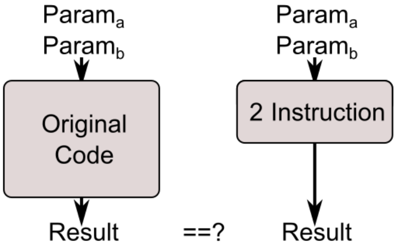
Super-optimisation
Massalin's super-optimiser

- Start with length k = 1
- Generate **all** instruction sequences of length k
- Run test cases to compare behaviour to original code



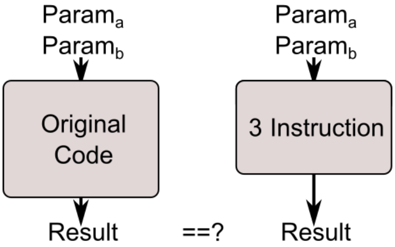
Super-optimisation
Massalin's super-optimiser

- Start with length $k = 1$
- Generate **all** instruction sequences of length k
- Run test cases to compare behaviour to original code
- If success, return sequence else increase length



Super-optimisation
Massalin's super-optimiser

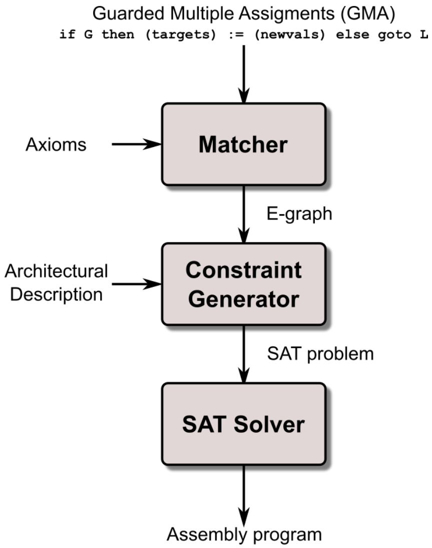
- Start with length $k = 1$
- Generate **all** instruction sequences of length k
- Run test cases to compare behaviour to original code
- If success, return sequence else increase length
- **Test cases not correctness guarantee**



Denali: A goal directed super-optimiser

- Super-optimiser. Attempt to find optimum code - not just improve.
- “Denali: A goal directed super-optimizer” PLDI 2002 by Joshi, Nelson and Randall. Expect you to read, understand and know this
- Based on theorem proving over all equivalent programs. Basic idea: use a set of axioms which define equivalent instructions
- Generate a data structure representing all possible equivalent programs. Then use a theorem prover to find the shortest sequence
- “There does not exist a program k cycles or less”. Searches all equivalence to disprove this. Theorem provers designed to be efficient at this type of search

Denali: A goal directed super-optimiser
Structure


Guarded Multiple Assigments (GMA)
if G then (targets) := (newvals) else goto L
Axioms
Matcher
E-graph
Architectural Description
Constraint Generator
SAT problem
SAT Solver
Assembly program

Denali: A goal directed super-optimiser
Axioms

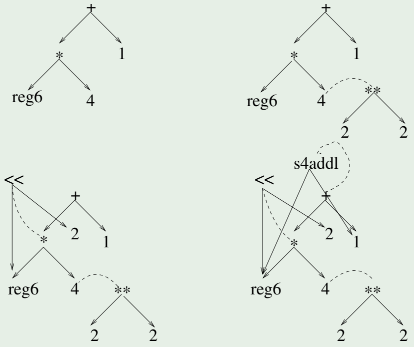
Axioms are a mixture of generic and machine specific for Alpha

- $4 = 2^2$ – generic
- $(\forall k, n :: k*2^n = k<<n)$ – machine specific
- $(\forall k, n :: k*4+n = \mathbf{s4addl}(k, n))$

Denali: A goal directed super-optimiser
E-graph

Equivalences represented in an E-graph.
$O(n)$ graph can represent $O(2^n)$ distinct ways of computing term

Match expression 1 + reg6 * 4



Dashed lines denote equivalences (matches)

Denali: A goal directed super-optimiser
Unknowns

Once equivalent programs represented, now need to see if there is a solution in K cycles.
Unknowns:

- $L(i, T)$ Term T started at time i
- $A(i, T)$ Term T finished at time i
- $B(i, Q)$ Equivalence class Q finished by time i

Need constraints to solve.
Let $\lambda(T) =$ latency of term T

Denali: A goal directed super-optimiser

Constraints

- $\bigwedge_{i,T}(L(i,T) \Leftrightarrow A(i+\lambda(T)-1,T))$ – arrives λ cycles after being launched
- $\bigwedge_{i,T}\bigwedge_{Q\in args(T)}(L(i,T) \Rightarrow B(i-1,Q))$ –operation cannot be launched till args ready
- $\bigwedge_{Q\in G})B(K-1,Q)$ – all terms in the goal must be finished within K cycles

Now test with a SAT solver setting K to a suitable number.
Generates excellent code
Finds best code fast. Approximate memory latency, limited implementation

Multimedia code

- Re-targetable code generation key issue in embedded processors
- Heterogeneous instruction sets. Restrictions on function units.
- Exploiting powerful multimedia instructions
- Standard Code generation seems completely blind to parallelism. Shorter code may severely restrict ILP
- Denali gets around this but expensive
- Multimedia instructions are often SIMD like. Need parallelisation techniques. Middle section of lectures.

Summary

- Naive translation and ILOC
- Cost based instruction selection
- Bottom up tiling on low level AST
- Alternative approach based on peephole optimisation
- Super-optimisation
- Multimedia code generation