

15-745 Lecture 5

Control flow analysis
Natural loops
Classical Loop Optimizations
Dependencies

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Based on slides from Lee & Callahan

Loops are Key

- Loops are **extremely** important
 - the "90-10" rule
- Loop optimization involves
 - understanding control-flow structure
 - Understanding data-dependence information
 - sensitivity to side-effecting operations
 - extra care in some transformations such as register spilling

Common loop optimizations

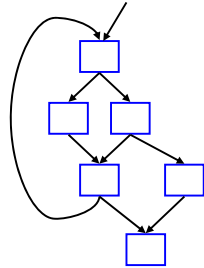
- | | |
|--|---|
| <ul style="list-style-type: none">• Hoisting of loop-invariant computations<ul style="list-style-type: none">- pre-compute before entering the loop• Elimination of induction variables<ul style="list-style-type: none">- change $p=i*w+b$ to $p=b, p+=w$, when w, b invariant• Loop unrolling<ul style="list-style-type: none">- to improve scheduling of the loop body | Scalar opts,
DF analysis,
Control flow analysis |
| <ul style="list-style-type: none">• Software pipelining<ul style="list-style-type: none">- To improve scheduling of the loop body• Loop permutation<ul style="list-style-type: none">- to improve cache memory performance | Requires
understanding
data
dependencies |

Finding Loops

- To optimize loops, we need to find them!
- Could use source language loop information in the abstract syntax tree...
- **BUT:**
 - There are multiple source loop constructs: for, while, do-while, even goto in C
 - Want IR to support different languages
 - Ideally, we want a single concept of a loop so all have same analysis, same optimizations
 - Solution: dismantle source-level constructs, then re-find loops from fundamentals

Finding Loops

- To optimize loops, we need to find them!
- Specifically:
 - loop-header node(s)
 - nodes in a loop that have immediate predecessors not in the loop
 - back edge(s)
 - control-flow edges to previously executed nodes
 - all nodes in the loop body



Control-flow analysis

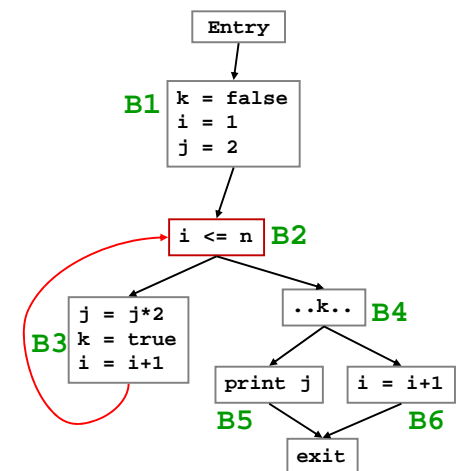
- Many languages have goto and other complex control, so loops can be hard to find in general
- Determining the control structure of a program is called **control-flow analysis**
- Based on the notion of **dominators**

Dominators

- a dom b
 - node a dominates b if every possible execution path from entry to b includes a
- a sdom b
 - a strictly dominates b if a dom b and a != b
- a idom b
 - a immediately dominates b if a sdom b, AND there is no c such that a sdom c and c sdom b

Back edges and loop headers

- A control-flow edge from node B3 to B2 is a **back edge** if B2 dom B3
- Furthermore, in that case node B2 is a **loop header**

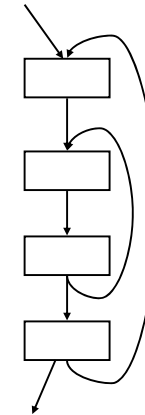


Natural loop

- Consider a back edge from node n to node h
- The natural loop of $n \rightarrow h$ is the set of nodes L such that for all $x \in L$:
 - $h \text{ dom } x$ and
 - there is a path from x to n not containing h

Examples

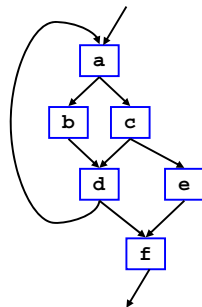
Simple example:



(often it's more complicated, since a FOR loop found in the source code might need an if/then guard)

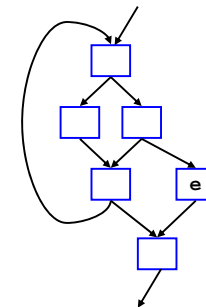
Examples

Try this:

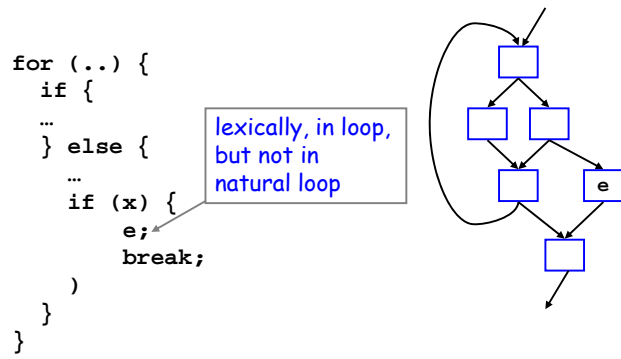


Examples

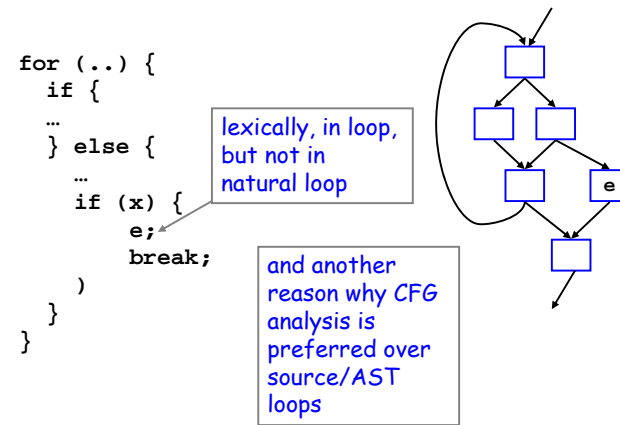
```
for (..) {  
  if {  
    ...  
  } else {  
    ...  
    if (x) {  
      e;  
      break;  
    }  
  }  
}
```



Examples

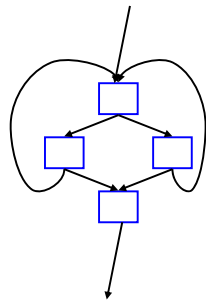


Examples



Examples

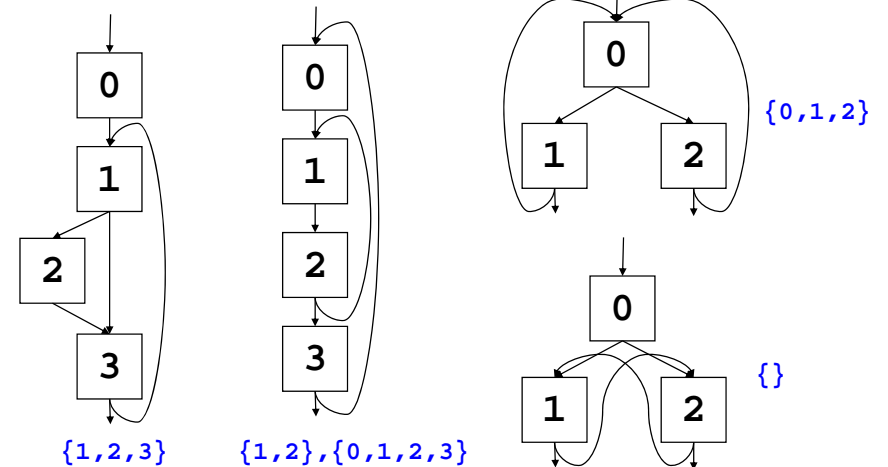
- Yes, it can happen in C



Natural Loops

One loop per header..

What are the natural loops?

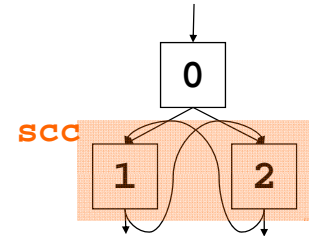


Nested Loops

- Unless two natural loops have the same header, they are either disjoint or **nested** within each other
- If A and B are loops (sets of blocks) with headers a and b such that $a \neq b$ and $b \in A$
 - $B \subset A$
 - loop B is **nested** within A
 - B is the **inner loop**
- Can compute the loop-nest tree

General Loops

- A more general looping structure is a **strongly connected component** of the control flow graph
 - subgraph $\langle N_{scc}, E_{scc} \rangle$ such that every block in N_{scc} is reachable from every other node using only edges in E_{scc}



Not very useful definition of a loop

Reducible Flow Graphs

There is a special class of flow graphs, called **reducible flow graphs**, for which several code-optimizations are especially easy to perform.

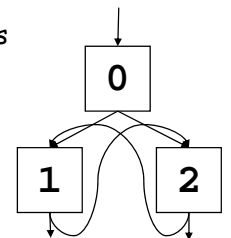
In reducible flow graphs loops are unambiguously defined and dominators can be efficiently computed.

Reducible flow graphs

Definition: A flow graph G is **reducible** iff we can partition the edges into two disjoint groups, **forward edges** and **back edges**, with the following two properties.

1. The forward edges form an acyclic graph in which every node can be reached from the initial node of G .
2. The back edges consist only of edges whose heads dominate their tails.

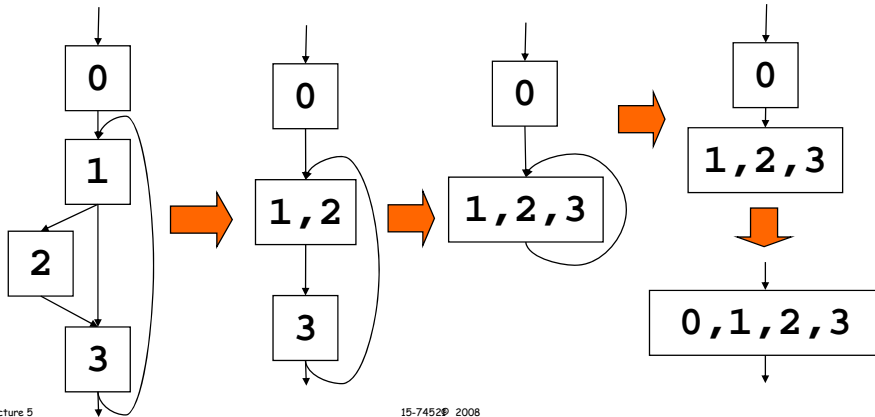
Why isn't this reducible?



This flow graph has **no back edges**. Thus, it would be reducible if the entire graph were acyclic, which is not the case.

Alternative definition

- **Definition:** A flow graph G is **reducible** if we can repeatedly collapse (reduce) together blocks (x,y) where x is the only predecessor of y (ignoring self loops) until we are left with a single node



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Properties of Reducible Flow Graphs

- In a reducible flow graph, **all loops are natural loops**
- Can use DFS to find loops
- Many analyses are more efficient
 - polynomial versus exponential

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Good News

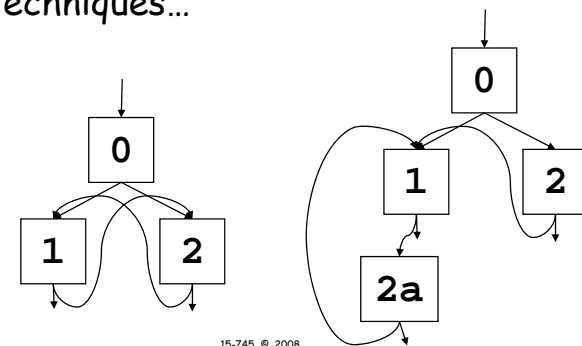
- Most flow graphs are reducible
- Languages prohibit irreducibility
 - goto free C
 - Java
- Programmers usually don't use such constructs even if they're available
 - >90% of old Fortran code reducible

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Dealing with Irreducibility

- Don't
- Can split nodes and duplicate code to get reducible graph
 - possible exponential blowup
- Other techniques...



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Loop optimizations: Hoisting of loop-invariant computations

Loop-invariant computations

- A definition $t = x \text{ op } y$ in a loop is (conservatively) loop-invariant if
 - x and y are constants, or
 - all reaching definitions of x and y are outside the loop, or
 - only one definition reaches x (or y), and that definition is loop-invariant
 - so keep marking iteratively

Loop-invariant computations

- Be careful:

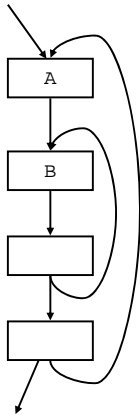
```
t = expr;
for () {
    s = t * 2;
    t = loop_invariant_expr;
    x = t + 2;
    ...
}
```

- Even though t 's two reaching expressions are each invariant, s is not invariant...

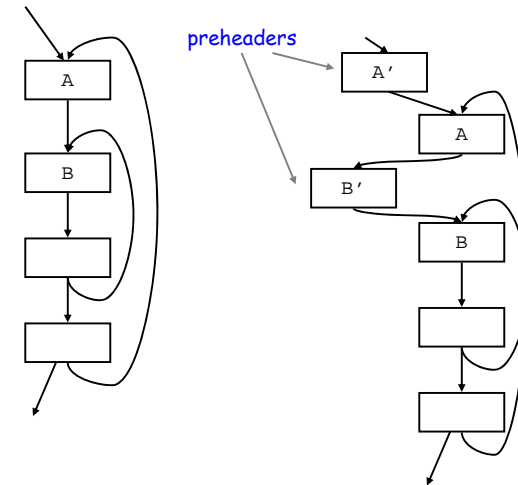
Hoisting

- In order to "hoist" a loop-invariant computation out of a loop, we need a place to put it
- We could copy it to all immediate predecessors (except along the back-edge) of the loop header...
- ...But we can avoid code duplication by inserting a new block, called the **pre-header**

Hoisting



Hoisting



Hoisting conditions

- For a loop-invariant definition $d: t = x \text{ op } y$
- we can hoist d into the loop's pre-header only if
 1. d 's block dominates all loop exits at which t is live-out, and
 2. d is only the only definition of t in the loop, and
 3. t is not live-out of the pre-header

We need to be careful...

- All hoisting conditions must be satisfied!

```

L0:
  t = 0
L1:
  i = i + 1
  t = a * b
  M[i] = t
  if i < N goto L1
L2:
  x = t
    
```

OK

```

L0:
  t = 0
L1:
  if i >= N goto L2
  i = i + 1
  t = a * b
  M[i] = t
  goto L1
L2:
  x = t
    
```

violates 1,3

```

L0:
  t = 0
L1:
  i = i + 1
  t = a * b
  M[i] = t
  t = 0
  M[j] = t
  if i < N goto L1
L2:
    
```

violates 2

We need to be careful...

- All hoisting conditions must be satisfied!

<pre>L0: t = 0 L1: i = i + 1 t = a * b M[i] = t if i < N goto L1 L2: x = t</pre>	<pre>L0: t = 0 L1: if i >= N goto L2 i = i + 1 t = a * b M[i] = t goto L1 L2: x = t</pre>	<pre>L0: t = 0 L1: i = i + 1 t = a * b M[i] = t t = 0 M[j] = t if i < N goto L1 L2:</pre>
OK	violates 1,3	violates 2

this def reaches


this def reaches

Loop optimizations:
Induction-variable
Strength reduction

The basic idea of IVE

- Suppose we have a loop variable
 - i initially 0; each iteration $i = i + 1$
- and a variable that linearly depends on it:
 - $x = i * c1 + c2$
- In such cases, we can try to
 - initialize $x = i_0 * c1 + c2$ (execute once)
 - increment x by $c1$ each iteration

Simple Example of IVE

<pre>for i = 0 to n a[i] = 0</pre>		<pre>H: i <- 0 if i >= n goto exit j <- i * 4 k <- j + a M[k] <- 0 i <- i + 1 goto H</pre>
--------------------------------------	---	--


Clearly, j & k do not need to be computed anew each time since they are related to i and i changes linearly.

Simple Example of IVE

```

H:
i <- 0
if i >= n goto exit
j <- i * 4
k <- j + a
M[k] <- 0
i <- i + 1
goto H

```



```

H:
i <- 0
j' <- 0
k' <- a
if i >= n goto exit
j <- j'
k <- k'
M[k] <- 0
i <- i + 1
j' <- j' + 4
k' <- k' + 4
goto H

```


But, then we don't even need j (or j')

Simple Example of IVE

```

H:
i <- 0
j' <- 0
k' <- a
if i >= n goto exit
j <- j'
k <- k'
M[k] <- 0
i <- i + 1
j' <- j' + 4
k' <- k' + 4
goto H

```



```

H:
i <- 0
k' <- a
if i >= n goto exit
k <- k'
M[k] <- 0
i <- i + 1
k' <- k' + 4
goto H

```

Do we need i?


Simple Example of IVE

Rewrite comparison

```

H:
i <- 0
k' <- a
if i >= n goto exit
k <- k'
M[k] <- 0
i <- i + 1
k' <- k' + 4
goto H

```



```

H:
i <- 0
k' <- a
if k' >= a+(n*4) goto exit
k <- k'
M[k] <- 0
k' <- k' + 4
goto H

```

But, $a+(n*4)$ is loop invariant


Simple Example of IVE

Invariant code motion on $a+(n*4)$

```

H:
i <- 0
k' <- a
if k' >= a+(n*4) goto exit
k <- k'
M[k] <- 0
k' <- k' + 4
goto H

```



```

H:
k' <- a
n' <- a + (n * 4)
if k' >= n' goto exit
k <- k'
M[k] <- 0
k' <- k' + 4
goto H


```

now, we do copy propagation and eliminate k

Simple Example of IVE

Copy propagation

```
H:
k' <- a
n' <- a + (n * 4)
if k' >= n' goto exit
k <- k'
M[k] <- 0
k' <- k' + 4
goto H
```



```
H:
k' <- a
n' <- a + (n * 4)
if k' >= n' goto exit
M[k'] <- 0
k' <- k' + 4
goto H
```

Voila!

Simple Example of IVE

Compare original and result of IVE

```
i <- 0
H:
if i >= n goto exit
j <- i * 4
k <- j + a
M[k] <- 0
i <- i + 1
goto H
```

```
k' <- a
n' <- a + (n * 4)
H:
if k' >= n' goto exit
M[k'] <- 0
k' <- k' + 4
goto H
```

Voila!

What we did

- identified induction variables (i,j,k)
- strength reduction (changed * into +)
- dead-code elimination (j <- j')
- useless-variable elimination (j' <- j' + 4) (This can also be done with ADCE)
- loop invariant identification & code-motion
- almost useless-variable elimination (i)
- copy propagation

Is it faster?

- On some hardware, adds are much faster than multiplies
- Furthermore, one fewer value is computed,
 - thus potentially saving a register
 - and decreasing the possibility of spilling

Loop preparation

- Before attempting IVE, it is best to first perform :
 - constant propagation & constant folding
 - copy propagation
 - loop-invariant hoisting

How to do it, step 1

- First, find the basic IVs
 - scan loop body for defs of the form
$$x = x + c \text{ or } x = x - c$$
where c is loop-invariant
 - record these basic IVs as
$$x = (x, 1, c)$$
 - this represents the IV: $x = x * 1 + c$

Representing IVs

- Characterize all induction variables by:
 - (base-variable, offset, multiple)
 - where the offset and multiple are loop-invariant
- IOW, after an induction variable is defined it equals:

offset + multiple * base-variable

How to do it, step 2

- Scan for derived IVs of the form
$$k = i * c1 + c2$$
 - where i is a basic IV,
this is the only def of k in the loop, and
 $c1$ and $c2$ are loop invariant
- We say k is in the family of i
- Record as $k = (i, c1, c2)$

How to do it, step 3

- Iterate, looking for derived IVs of the form
$$k = j * c1 + c2$$
 - where IV $j = (i, a, b)$, and
 - this is the only def of k in the loop, and
 - there is no def of i between the def of j and the def of k
 - $c1$ and $c2$ are loop invariant
- Record as $k = (i, a*c1, b*c1+c2)$

Simple Example of IVE

```
i <- 0
H:
  if i >= n goto exit
  j <- i * 4
  k <- j + a
  M[k] <- 0
  i <- i + 1
  goto H

i: (i, 1, 1) i.e., i = 1 + 1 * i
j: (i, 0, 4) i.e., j = 0 + 4 * i
k: (i, a, 4) i.e., k = a + 4 * i
```

So, j & k are in family of i

Finding the IVs

- Maintain three tables: basic & maybe & other
- Find basic Ivs:
Scan stmts. If var \notin maybe, and of proper form, put into basic. Otherwise, put var in other and remove from maybe.
- Find compound Ivs:
 - If var defined more than once, put into other
 - For all stmts of proper form that use a basic IV

» FIX THIS SLIDE

How to do it, step 4

- This is the strength reduction step
- For an induction variable $k = (i, c1, c2)$
 - initialize $k = i * c1 + c2$ in the preheader
 - replace k 's def in the loop by
$$k = k + c1$$
 - make sure to do this after i 's def

How to do it, step 5

- This is the comparison rewriting step
- For an induction variable $k = (i, a_k, b_k)$
 - If k used only in definition and comparison
 - There exists another variable, j , in the same class and is not "useless" and $j = (i, a_j, b_j)$
- Rewrite $k < n$ as
$$j < (b_j/b_k)(n-a_k)+a_j$$
- Note: since they are in same class:
$$(j-a_j)/b_j = (k-a_k)/b_k$$

Notes

- Are the c_1, c_2 constant, or just invariant?
 - if constant, then you can keep folding them: they're always a constant even for derived IVs
 - otherwise, they can be expressions of loop-invariant variables
- But if constant, can find IVs of the type
$$x = i/b$$
and know that it's legal, if b evenly divides the stride...

Is it faster? (2)

- On some hardware, adds are much faster than multiplies
- But...not always a win!
 - Constant multiplies might otherwise be reduced to shifts/adds that result in even better code than IVE
 - Scaling of addresses ($i*4$) might come for free on your processor's address modes
- So maybe: only convert $i*c_1+c_2$ when c_1 is loop invariant but not a constant

Common loop optimizations

- Hoisting of loop-invariant computations
 - pre-compute before entering the loop
- Elimination of induction variables
 - change $p=i*w+b$ to $p=b, p+=w$, when w, b invariant
- Loop unrolling
 - to improve scheduling of the loop body

- Software pipelining
 - To improve scheduling of the loop body
- Loop permutation
 - to improve cache memory performance

Requires understanding data dependencies

Dependencies in Loops

- **Loop independent** data dependence occurs between accesses in the **same** loop iteration.
- **Loop-carried** data dependence occurs between accesses across **different** loop iterations.
- There is data dependence between access **a** at iteration **i-k** and access **b** at iteration **i** when:
 - **a** and **b** access the same memory location
 - There is a path from **a** to **b**
 - Either **a** or **b** is a write

Defining Dependencies

- Flow Dependence $W \rightarrow R \quad \delta^f$ } true
- Anti-Dependence $R \rightarrow W \quad \delta^a$ } false
- Output Dependence $W \rightarrow W \quad \delta^o$ }

```

S1) a=0;
S2) b=a;
S3) c=a+d+e;
S4) d=b;
S5) b=5+e;
    
```

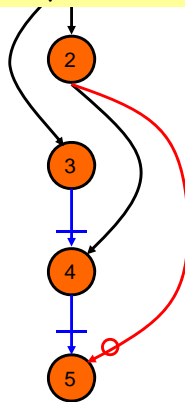
Example Dependencies

```

S1) a=0;
S2) b=a;
S3) c=a+d+e;
S4) d=b;
S5) b=5+e;
    
```

These are scalar dependencies. The same idea holds for memory accesses.

source	type	target	due to
S1	δ^f	S2	a
S1	δ^f	S3	a
S2	δ^f	S4	b
S3	δ^a	S4	d
S4	δ^a	S5	b
S2	δ^o	S5	b



What can we do with this information?
 What are anti- and flow- called "false" dependences?

Data Dependence in Loops

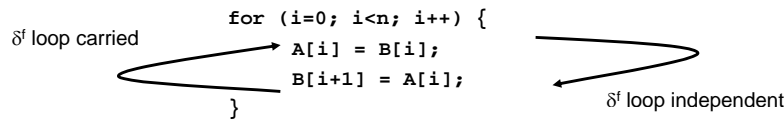
- Dependence can flow across iterations of the loop.
- Dependence information is annotated with iteration information.
- If dependence is across iterations it is **loop carried** otherwise **loop independent**.

```

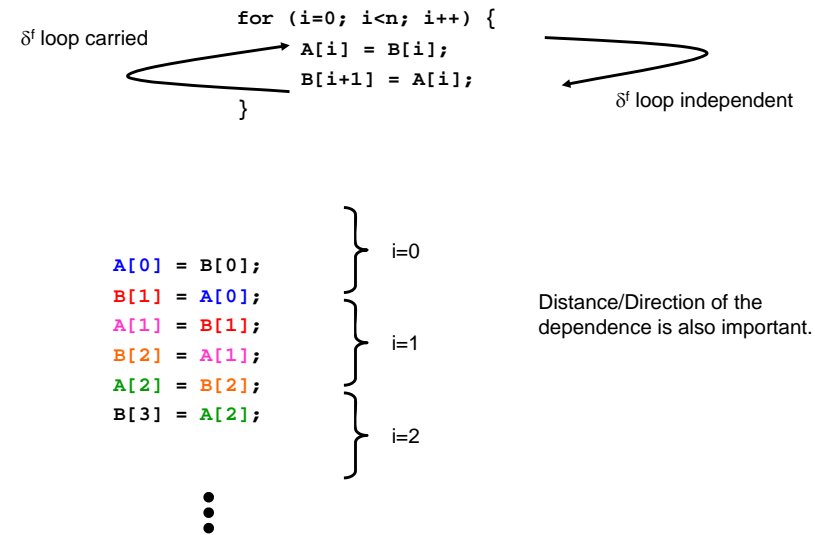
for (i=0; i<n; i++) {
    A[i] = B[i];
    B[i+1] = A[i];
}
    
```

Data Dependence in Loops

- Dependence can flow across iterations of the loop.
- Dependence information is annotated with iteration information.
- If dependence is across iterations it is **loop carried** otherwise **loop independent**.

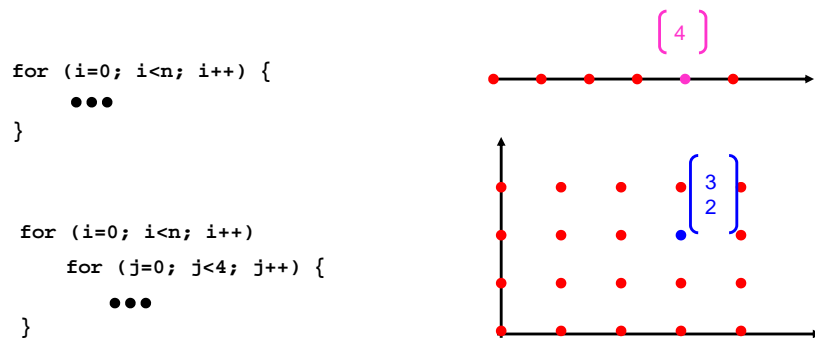


Unroll Loop to Find Dependencies



Iteration Space

Every iteration generates a point in an n-dimensional space, where n is the depth of the loop nest.



Distance Vector

```

for (i=0; i<n; i++) {
    A[i] = B[i];
    B[i+1] = A[i];
}
    
```

```

A[0] = B[0];
B[1] = A[0];
A[1] = B[1];
B[2] = A[1];
A[2] = B[2];
B[3] = A[2];
    
```

Distance vector is the difference between the target and source iterations.

$$d = I_t - I_s$$

Exactly the distance of the dependence, i.e.,

$$I_s + d = I_t$$

Example of Distance Vectors

```

for (i=0; i<n; i++)
  for (j=0; j<m; j++){
    A[i,j] = ;
    = A[i,j];
    B[i,j+1] = ;
    = B[i,j];
    C[i+1,j] = ;
    = C[i,j+1] ;
  }

```

$A_{0,2} = A_{0,2}$	$A_{1,2} = A_{1,2}$	$A_{2,2} = A_{2,2}$
$B_{0,3} = B_{0,2}$	$B_{1,3} = B_{1,2}$	$B_{2,3} = B_{2,2}$
$C_{1,2} = C_{0,3}$	$C_{2,2} = C_{1,3}$	$C_{3,2} = C_{2,3}$
$A_{0,1} = A_{0,1}$	$A_{1,1} = A_{1,1}$	$A_{2,1} = A_{2,1}$
$B_{0,2} = B_{0,1}$	$B_{1,2} = B_{1,1}$	$B_{2,2} = B_{2,1}$
$C_{1,1} = C_{0,2}$	$C_{2,1} = C_{1,2}$	$C_{3,1} = C_{2,2}$
$A_{0,0} = A_{0,0}$	$A_{1,0} = A_{1,0}$	$A_{2,0} = A_{2,0}$
$B_{0,1} = B_{0,0}$	$B_{1,1} = B_{1,0}$	$B_{2,1} = B_{2,0}$
$C_{1,0} = C_{0,1}$	$C_{2,0} = C_{1,1}$	$C_{3,0} = C_{2,1}$

i

Example of Distance Vectors

```

for (i=0; i<n; i++)
  for (j=0; j<m; j++){
    A[i,j] = ;
    = A[i,j];
    B[i,j+1] = ;
    = B[i,j];
    C[i+1,j] = ;
    = C[i,j+1] ;
  }

```

$A_{0,2} = A_{0,2}$	$A_{1,2} = A_{1,2}$	$A_{2,2} = A_{2,2}$
$B_{0,3} = B_{0,2}$	$B_{1,3} = B_{1,2}$	$B_{2,3} = B_{2,2}$
$C_{1,2} = C_{0,3}$	$C_{2,2} = C_{1,3}$	$C_{3,2} = C_{2,3}$
$A_{0,1} = A_{0,1}$	$A_{1,1} = A_{1,1}$	$A_{2,1} = A_{2,1}$
$B_{0,2} = B_{0,1}$	$B_{1,2} = B_{1,1}$	$B_{2,2} = B_{2,1}$
$C_{1,1} = C_{0,2}$	$C_{2,1} = C_{1,2}$	$C_{3,1} = C_{2,2}$
$A_{0,0} = A_{0,0}$	$A_{1,0} = A_{1,0}$	$A_{2,0} = A_{2,0}$
$B_{0,1} = B_{0,0}$	$B_{1,1} = B_{1,0}$	$B_{2,1} = B_{2,0}$
$C_{1,0} = C_{0,1}$	$C_{2,0} = C_{1,1}$	$C_{3,0} = C_{2,1}$

A yields: $\begin{pmatrix} 0 \\ 0 \end{pmatrix}$

B yields: $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$

C yields: $\begin{pmatrix} 1 \\ -1 \end{pmatrix}$

i

Data Dependences

Loop carried: between two statements instances in two different iterations of a loop.

Loop independent: between two statements instances in the same loop iteration.

Lexically forward: the source comes before the target.

Lexically backward: otherwise.

The right-hand side of an assignment is considered to precede the left-hand side.

Review of Linear Algebra Lexicographic Order

Two n -vectors \mathbf{a} and \mathbf{b} are equal, $\mathbf{a} = \mathbf{b}$, if $a_i = b_i$, $1 \leq i \leq n$.

We say that \mathbf{a} is less than \mathbf{b} , $\mathbf{a} < \mathbf{b}$, if $a_i < b_i$, $1 \leq i \leq n$.

We say that \mathbf{a} is lexicographically less than \mathbf{b} , at level j , $\mathbf{a} \ll_j \mathbf{b}$, if $a_i = b_i$, $1 \leq i < j$ and $a_j < b_j$.

We say that \mathbf{a} is lexicographically less than \mathbf{b} , $\mathbf{a} \ll \mathbf{b}$, if there is a j , $1 \leq j \leq n$, such that $\mathbf{a} \ll_j \mathbf{b}$.

Lexicographic Order

Example of vectors

Consider the vectors **a** and **b** below :

$$\mathbf{a} = \begin{bmatrix} 1 \\ -1 \\ 0 \\ 2 \end{bmatrix} \quad \mathbf{b} = \begin{bmatrix} 1 \\ -1 \\ 1 \\ -1 \end{bmatrix}$$

We say that **a** is lexicographically less than **b** at level 3, $\mathbf{a} \prec_3 \mathbf{b}$, or simply that $\mathbf{a} \prec \mathbf{b}$.

Both **a** and **b** are lexicographically positive because $\mathbf{0} \prec \mathbf{a}$, and $\mathbf{0} \prec \mathbf{b}$.

Properties of Lexicographic Order

Let $n \geq 1$, and **i**, **j**, **k** denote arbitrary vectors in \mathbb{R}^n

- 1 For each u in $1 \leq u \leq n$, the relation \ll_u in \mathbb{R}^n is irreflexive and transitive.
- 2 The n relations \ll_u are pairwise disjoint:
 $i \ll_u j$ and $i \ll_v j$ imply that $u = v$.
- 3 If $i \neq j$, there is a unique integer u such that $1 \leq u \leq n$ and exactly one of the following two conditions holds:
 $i \ll_u j$ or $j \ll_u i$.
- 4 $i \ll_u j$ and $j \ll_v k$ together imply that $i \ll_w k$, where $w = \min(u, v)$.

Data Dependence in Loops

An Example

Find the dependence relations due to the array X in the program below:

```
(S1) for i = 2 to 9 do
(S2)   X[i] = Y[i] + Z[i]
(S3)   A[i] = X[i-1] + 1
(S4) end for
```

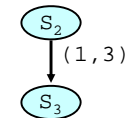
Solution

To find the data dependence relations in a simple loop, we can unroll the loop and see which statement instances depend on which others:

	i = 2	i = 3	i = 4
(s2)	X[2]=Y[2]+Z[2]	X[3]=Y[3]+Z[3]	X[4]=Y[4]+Z[4]
(s3)	A[2]=X[1]+1	A[3]=X[2]+1	A[4]=X[3]+1

Data Dependence in Loops

```
(S1) for i = 2 to
9 do
(S2)   X[i] =
Y[i] + Z[i]
(S3)   A[i] =
X[i-1] + 1
(S4) end for
```



Data dependence graph for statements in a loop (1,3) := iteration distance is 1, latency is 3.

	i = 2	i = 3	i = 4
(s2)	X[2]=Y[2]+Z[2]	X[3]=Y[3]+Z[3]	X[4]=Y[4]+Z[4]
(s3)	A[2]=X[1]+1	A[3]=X[2]+1	A[4]=X[3]+1

There is a *loop-carried, lexically forward, flow dependence* from S_2 to S_3 .