CSC D70: Compiler Optimization Prefetching

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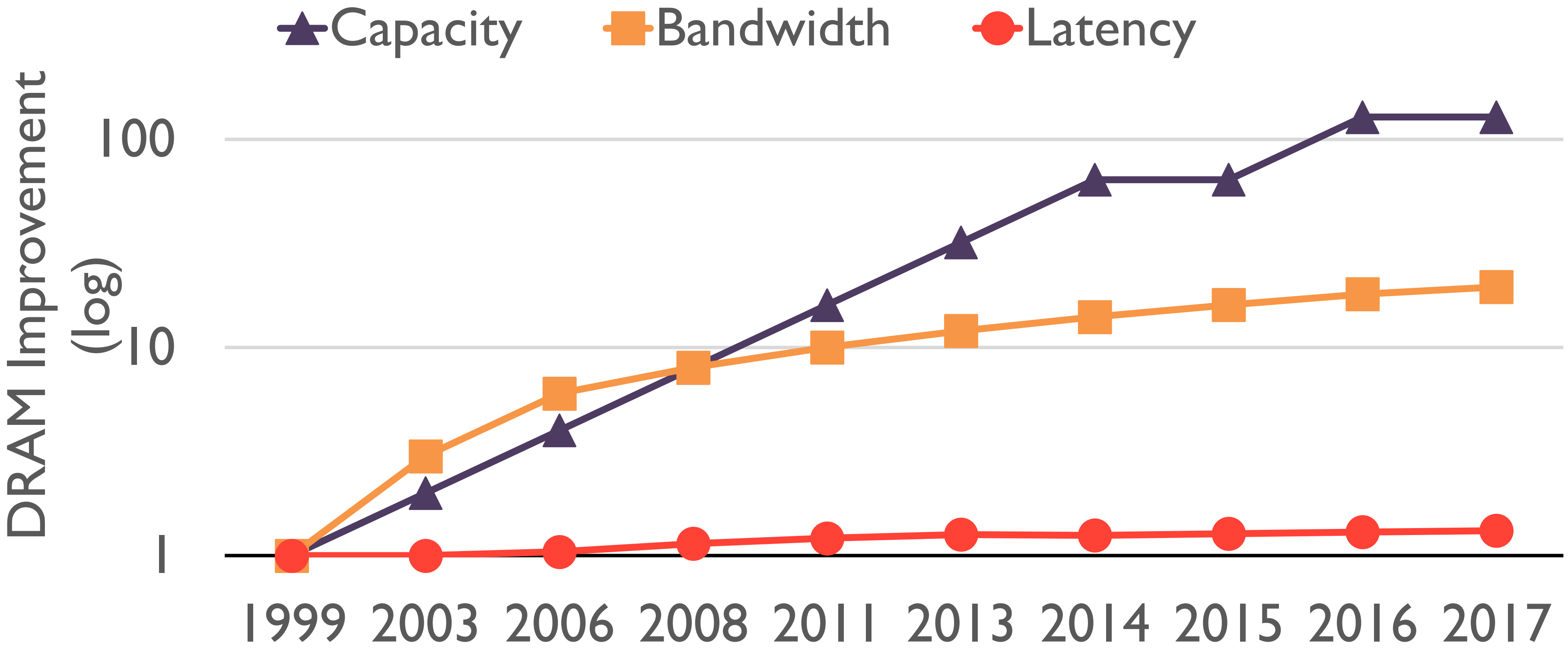
The content of this lecture is adapted from the lectures of Todd Mowry and Phillip Gibbons

No Lecture on April 5th

- I will be involved in MLSys 2021 conference

The Memory Latency Problem



- ↑ processor speed >> ↑ memory speed
- caches are not a panacea

Prefetching for Arrays: Overview

- Tolerating Memory Latency
- Prefetching Compiler Algorithm and Results
- Implications of These Results

Coping with Memory Latency

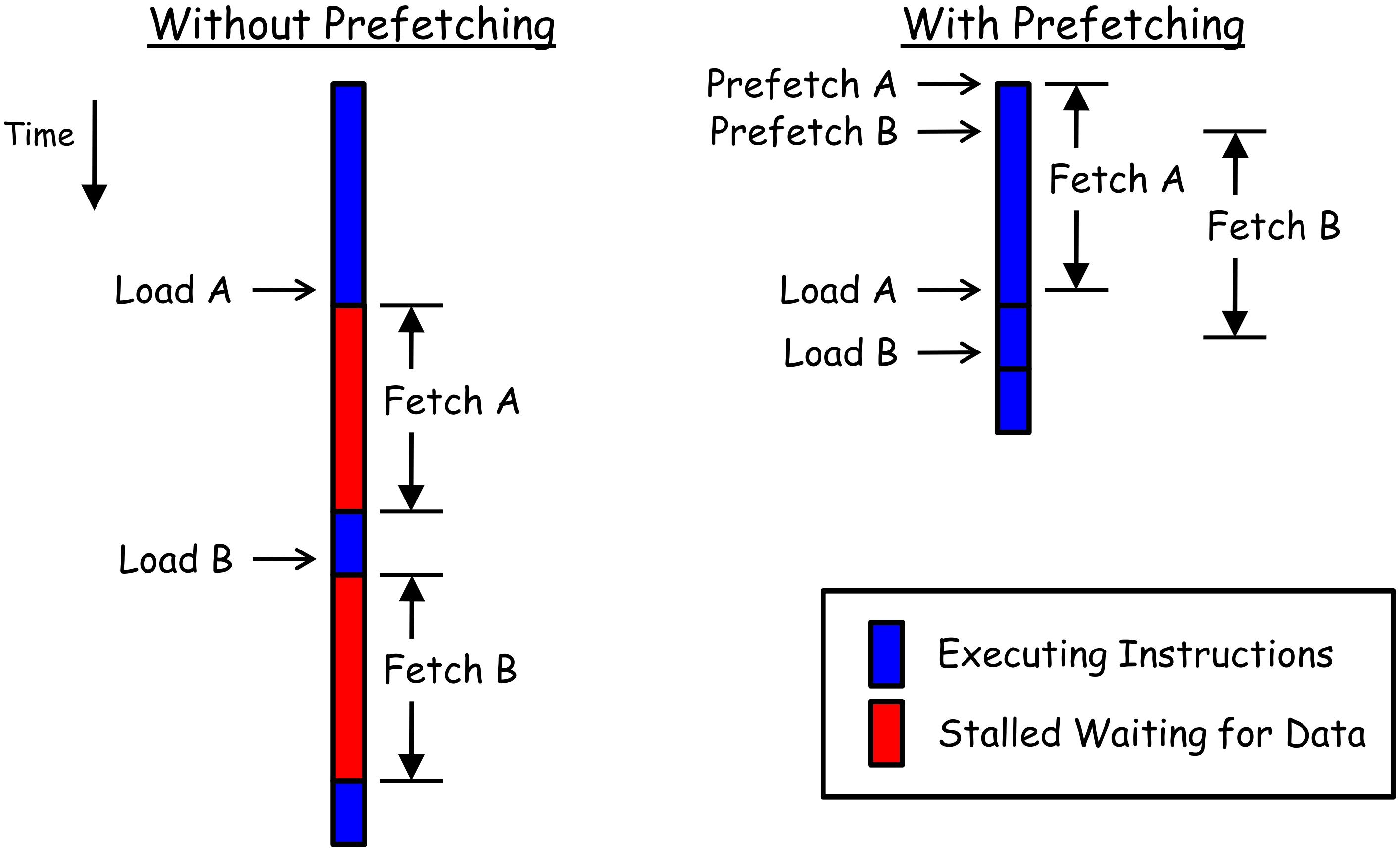
Reduce Latency:

- Locality Optimizations
  - reorder iterations to improve cache reuse

Tolerate Latency:

- Prefetching
  - move data close to the processor before it is needed

Tolerating Latency Through Prefetching



Without Prefetching

Time

Load A

Fetch A

Load B

Fetch B

With Prefetching

Prefetch A

Prefetch B

Fetch A

Fetch B

Load A

Load B

🟦 Executing Instructions

🟥 Stalled Waiting for Data

- overlap memory accesses with computation and other accesses

Types of Prefetching

Cache Blocks:

- (-) limited to unit-stride accesses

Nonblocking Loads:

- (-) limited ability to move back before use

Hardware-Controlled Prefetching:

- (-) limited to constant-strides and by branch prediction
- (+) no instruction overhead

Software-Controlled Prefetching:

- (-) software sophistication and overhead
- (+) minimal hardware support and broader coverage

Prefetching Goals

- Domain of Applicability
- Performance Improvement
  - maximize benefit
  - minimize overhead

Prefetching Concepts

possible only if addresses can be determined ahead of time
coverage factor = fraction of misses that are prefetched
unnecessary if data is already in the cache
effective if data is in the cache when later referenced

Analysis: what to prefetch

- maximize coverage factor
- minimize unnecessary prefetches

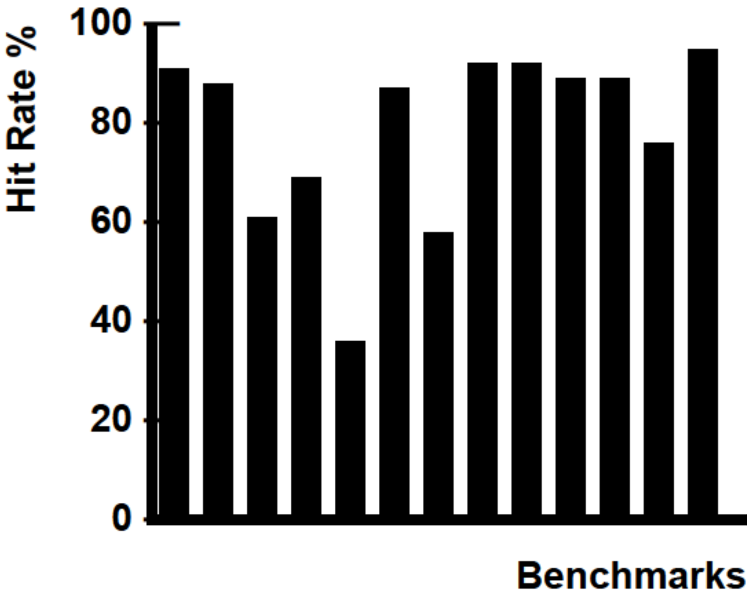
Scheduling: when/how to schedule prefetches

- maximize effectiveness
- minimize overhead per prefetch

Reducing Prefetching Overhead

- instructions to issue prefetches
- extra demands on memory system

Hit Rates for Array Accesses



- important to minimize unnecessary prefetches

Compiler Algorithm

Analysis: what to prefetch

- Locality Analysis

Scheduling: when/how to issue prefetches

- Loop Splitting
- Software Pipelining

Steps in Locality Analysis

1. Find data reuse
   - if caches were infinitely large, we would be finished

2. Determine “localized iteration space”
   - set of inner loops where the data accessed by an iteration is expected to fit within the cache

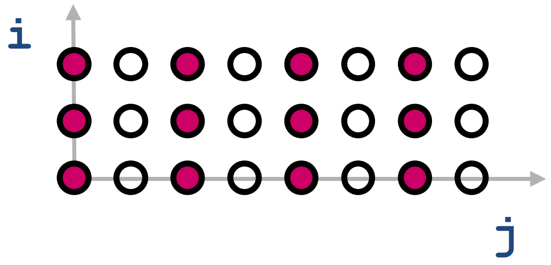
3. Find data locality:
   - reuse $\cap$ localized iteration space $\Rightarrow$ locality

Data Locality Example

```
for i = 0 to 2
 for j = 0 to 100
  A[i][j] = B[j][0] + B[j+1][0];
```

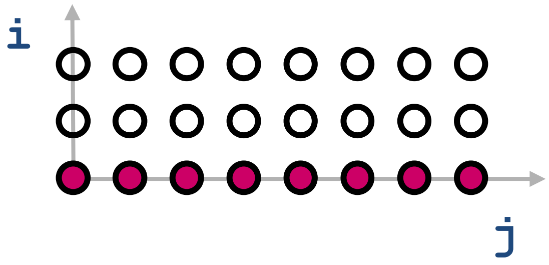
○ Hit
● Miss

A[i][j]



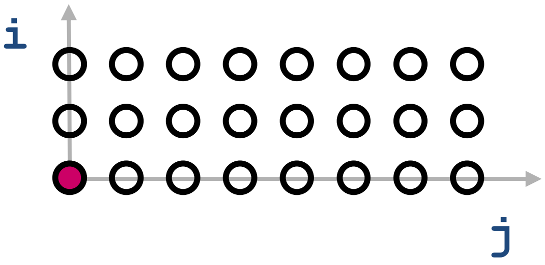
Spatial

B[j+1][0]



Temporal

B[j][0]



Group

Reuse Analysis: Representation

```
for i = 0 to 2
 for j = 0 to 100
  A[i][j] = B[j][0] + B[j+1][0];
```

- Map *n* loop indices into *d* array indices via array indexing function:

$$\vec{f}(\vec{\imath}) = H\vec{\imath} + \vec{c}$$

$$\begin{aligned}
\texttt{A[i][j]} &= \texttt{A}\left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} i \\ j \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix}\right) \\
\texttt{B[j][0]} &= \texttt{B}\left(\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} i \\ j \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix}\right) \\
\texttt{B[j+1][0]} &= \texttt{B}\left(\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} i \\ j \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix}\right)
\end{aligned}$$

Finding Temporal Reuse

- Temporal reuse occurs between iterations $\vec{\imath}_1$ and $\vec{\imath}_2$ whenever:

$$H\vec{\imath}_1 + \vec{c} = H\vec{\imath}_2 + \vec{c}$$

$$H(\vec{\imath}_1 - \vec{\imath}_2) = \vec{0}$$

- Rather than worrying about individual values $\vec{\imath}_1$ of $\vec{\imath}_2$ and, we say that reuse occurs along direction $\vec{r}$ vector when:

$$H(\vec{r}) = \vec{0}$$

- Solution: compute the *nullspace* of *H*

Temporal Reuse Example

```
for i = 0 to 2
 for j = 0 to 100
  A[i][j] = B[j][0] + B[j+1][0];
```

- Reuse between iterations (i_1,j_1) and (i_2,j_2) whenever:

$$\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_1 \\ j_1 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_2 \\ j_2 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_1 - i_2 \\ j_1 - j_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

- True whenever $j_1 = j_2$, and regardless of the difference between i_1 and i_2.
  - i.e. whenever the difference lies along the nullspace of $\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$
  - which is span{(1,0)} (i.e. the outer loop).

Prefetch Predicate

Locality Type	Miss Instance	Predicate
None	Every Iteration	True
Temporal	First Iteration	i = 0
Spatial	Every l iterations (l = cache line size)	(i mod l) = 0

Example:

```
for i = 0 to 2
  for j = 0 to 100
    A[i][j] = B[j][0] + B[j+1][0];
```

Reference	Locality	Predicate
A[i][j]	$\begin{bmatrix} i \\ j \end{bmatrix} = \begin{bmatrix} \text{none} \\ \text{spatial} \end{bmatrix}$	(j mod 2) = 0
B[j+1][0]	$\begin{bmatrix} i \\ j \end{bmatrix} = \begin{bmatrix} \text{temporal} \\ \text{none} \end{bmatrix}$	i = 0

Compiler Algorithm

Analysis: what to prefetch

- Locality Analysis

Scheduling: when/how to issue prefetches

- Loop Splitting
- Software Pipelining

Loop Splitting

- Decompose loops to isolate cache miss instances
  - cheaper than inserting IF statements

Locality Type	Predicate	Loop Transformation
None	True	None
Temporal	`i` = 0	Peel loop `i`
Spatial	(`i` mod l) = 0	Unroll loop `i` by l

- Apply transformations recursively for nested loops
- Suppress transformations when loops become too large
  - avoid code explosion

Software Pipelining

Iterations Ahead = $\left\lceil \frac{l}{s} \right\rceil$

where l = memory latency, s = shortest path through loop body

Original Loop

```
for (i = 0; i<100; i++)
   a[i] = 0;
```

Software Pipelined Loop
(5 iterations ahead)

```
for (i = 0; i<5; i++)       /* Prolog */
   prefetch(&a[i]);

for (i = 0; i<95; i++) { /* Steady State*/
   prefetch(&a[i+5]);
   a[i] = 0;
}

for (i = 95; i<100; i++)  /* Epilog */
   a[i] = 0;
```

Example Revisited

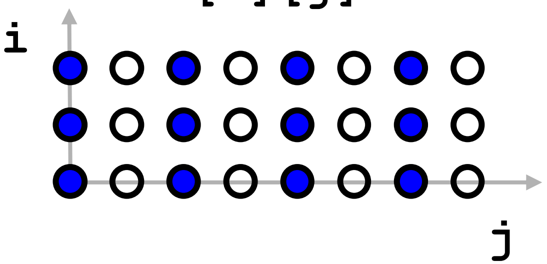
Original Code

```
for (i = 0; i < 3; i++)
  for (j = 0; j < 100; j++)
    A[i][j] = B[j][0] + B[j+1][0];
```

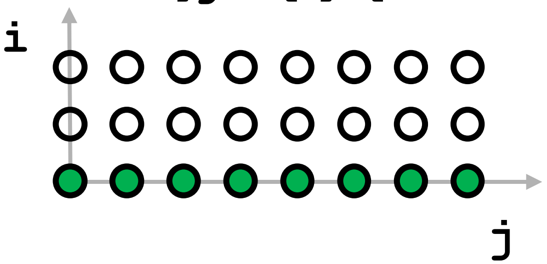
○ Cache Hit

● ● Cache Miss

A[i][j]



B[j+1][0]



Code with Prefetching

i = 0

```
prefetch(&A[0][0]);
for (j = 0; j < 6; j += 2) {
  prefetch(&B[j+1][0]);
  prefetch(&B[j+2][0]);
  prefetch(&A[0][j+1]);
}
for (j = 0; j < 94; j += 2) {
  prefetch(&B[j+7][0]);
  prefetch(&B[j+8][0]);
  prefetch(&A[0][j+7]);
  A[0][j] = B[j][0]+B[j+1][0];
  A[0][j+1] = B[j+1][0]+B[j+2][0];
}
for (j = 94; j < 100; j += 2) {
  A[0][j] = B[j][0]+B[j+1][0];
  A[0][j+1] = B[j+1][0]+B[j+2][0];
}
```

i > 0

```
for (i = 1; i < 3; i++) {
  prefetch(&A[i][0]);
  for (j = 0; j < 6; j += 2)
    prefetch(&A[i][j+1]);
  for (j = 0; j < 94; j += 2) {
    prefetch(&A[i][j+7]);
    A[i][j] = B[j][0] + B[j+1][0];
    A[i][j+1] = B[j+1][0] + B[j+2][0];
  }
  for (j = 94; j < 100; j += 2) {
    A[i][j] = B[j][0] + B[j+1][0];
    A[i][j+1] = B[j+1][0] + B[j+2][0];
  }
}
```

Prefetching Indirections

```
for (i = 0; i<100; i++)
   sum += A[index[i]];
```

Analysis: what to prefetch

- both dense and indirect references
- difficult to predict whether indirections hit or miss

Scheduling: when/how to issue prefetches

- modification of software pipelining algorithm

Software Pipelining for Indirections

Original Loop

```
for (i = 0; i<100; i++)
   sum += A[index[i]];
```

Software Pipelined Loop
(5 iterations ahead)

```
for (i = 0; i<5; i++)        /* Prolog 1 */
   prefetch(&index[i]);

for (i = 0; i<5; i++) {      /* Prolog 2 */
   prefetch(&index[i+5]);
   prefetch(&A[index[i]]);
}
for (i = 0; i<90; i++) {  /* Steady State*/
   prefetch(&index[i+10]);
   prefetch(&A[index[i+5]]);
   sum += A[index[i]];
}
for (i = 90; i<95; i++) {  /* Epilog 1 */
   prefetch(&A[index[i+5]]);
   sum += A[index[i]];
}
for (i = 95; i<100; i++)    /* Epilog 2 */
   sum += A[index[i]];
```

Summary of Results

Dense Matrix Code:

- eliminated 50% to 90% of memory stall time
- overheads remain low due to prefetching selectively
- significant improvements in overall performance (6 over 45%)

Indirections, Sparse Matrix Code:

- expanded coverage to handle some important cases

Prefetching for Arrays: Concluding Remarks

- Demonstrated that software prefetching is effective
  - selective prefetching to eliminate overhead
  - dense matrices and indirections / sparse matrices
  - uniprocessors and multiprocessors

- Hardware should focus on providing sufficient memory bandwidth

Prefetching for Recursive Data Structures

Recursive Data Structures

- Examples:
  - linked lists, trees, graphs, ...
- A common method of building large data structures
  - especially in non-numeric programs
- Cache miss behavior is a concern because:
  - large data set with respect to the cache size
  - temporal locality may be poor
  - little spatial locality among consecutively-accessed nodes

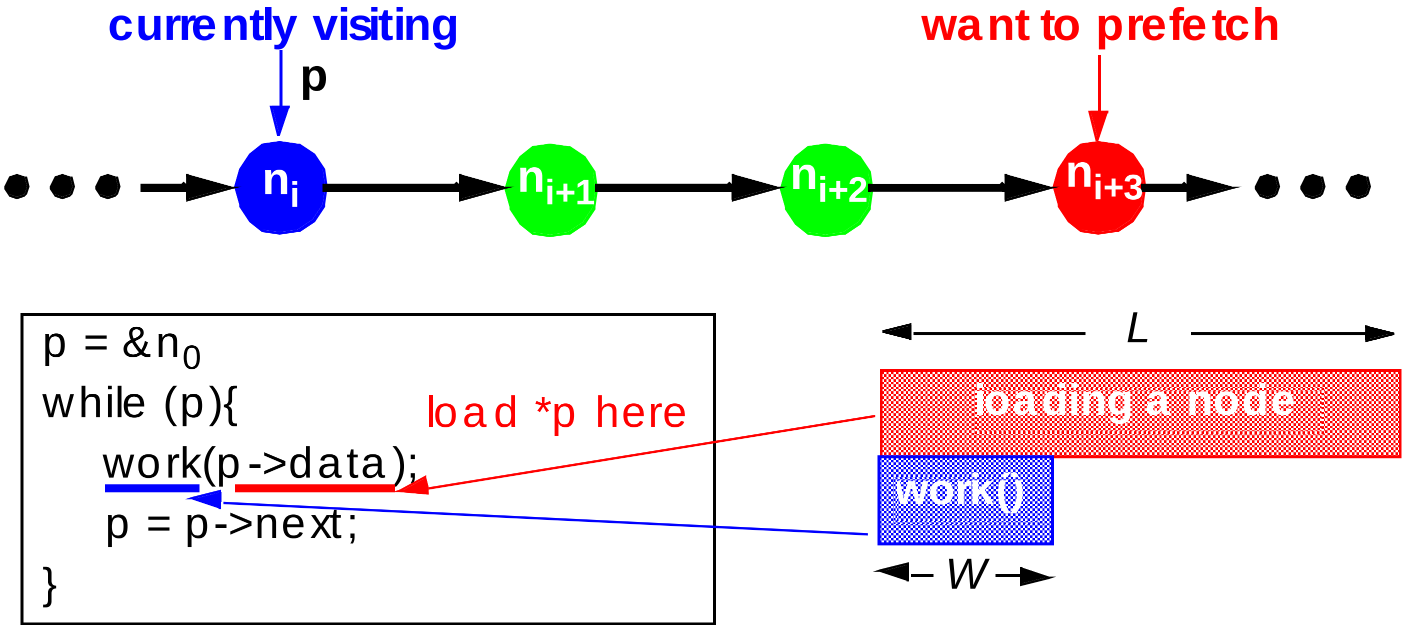
Goal:

- Automatic Compiler-Based Prefetching for Recursive Data Structures

Overview

- Challenges in Prefetching Recursive Data Structures
- Three Prefetching Algorithms
- Experimental Results
- Conclusions

Scheduling Prefetches for Recursive Data Structures



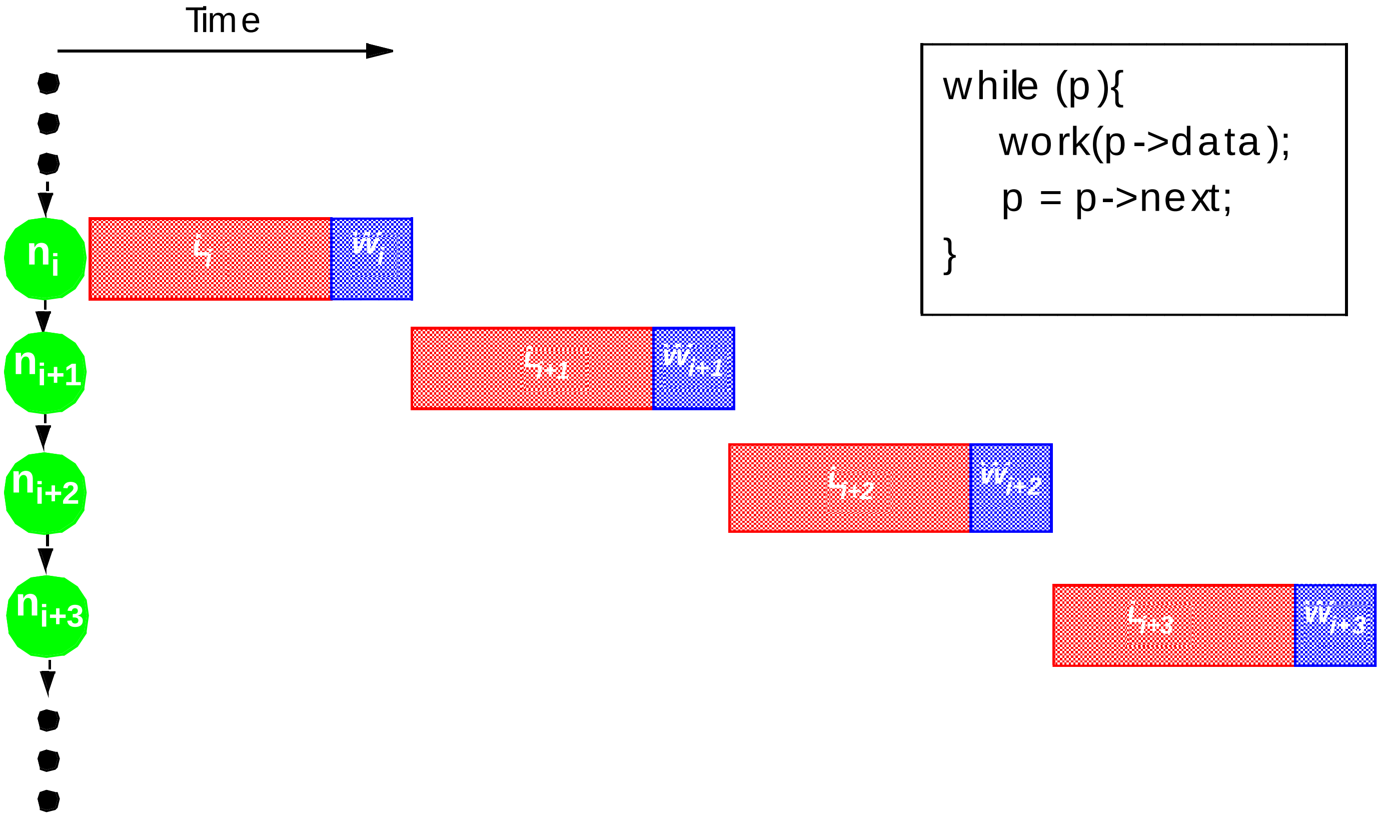
```
p = &n0
while (p){
    work(p->data);
    p = p->next;
}
```

Our Goal: *fully hide latency*

- thus achieving fastest possible computation rate of 1/W

- e.g., if L = 3W, we must prefetch 3 nodes ahead to achieve this

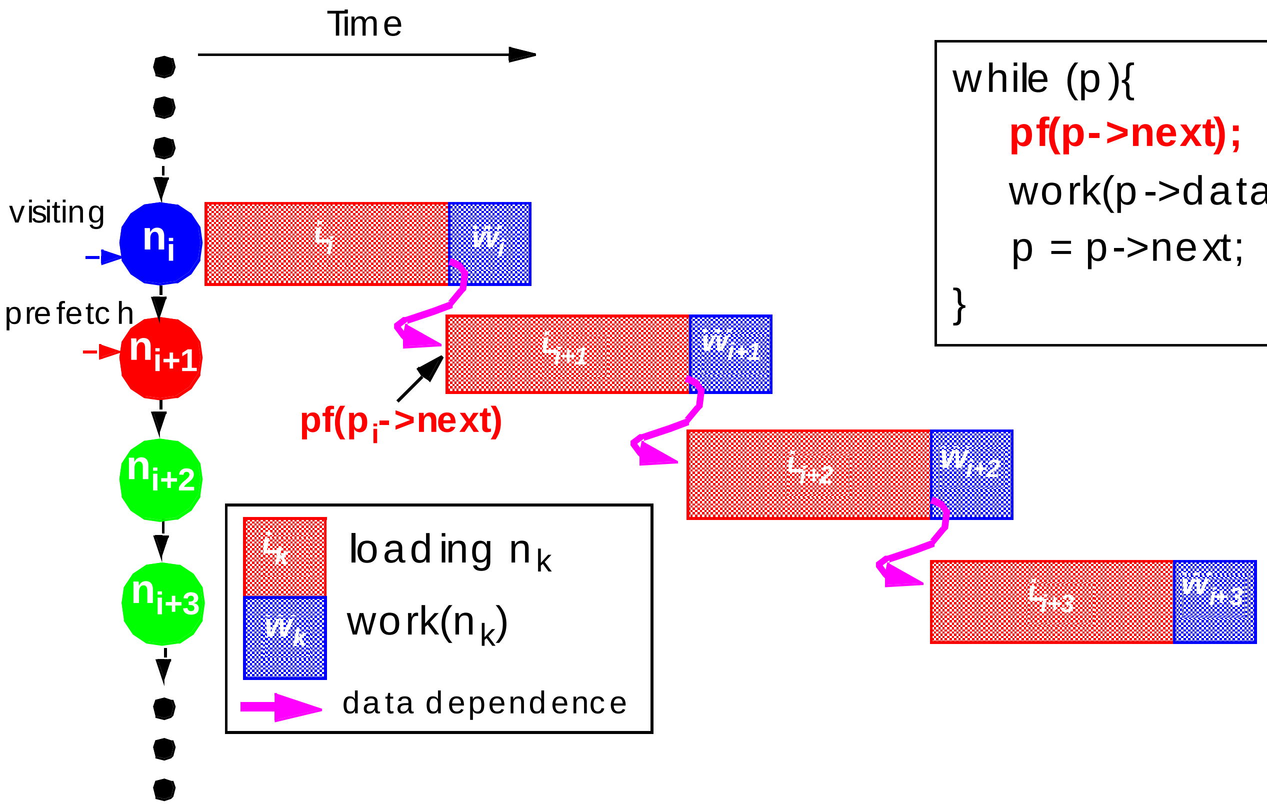
Performance without Prefetching



```
while (p){
    work(p->data);
    p = p->next;
}
```

computation rate = 1 / (L+W)

Prefetching One Node Ahead

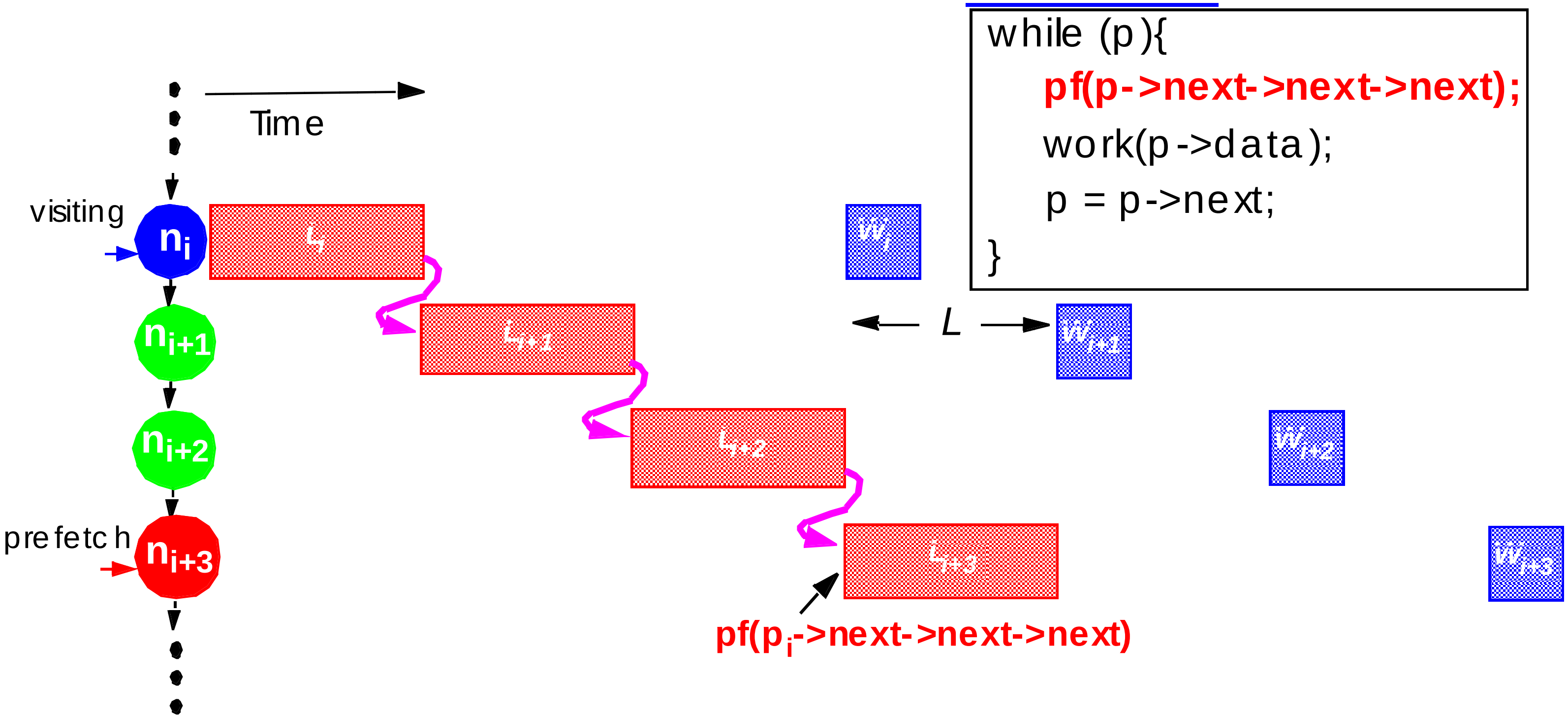


```
while (p){
    pf(p->next);
    work(p->data);
    p = p->next;
}
```

- Computation is overlapped with memory accesses

computation rate = 1/L

Prefetching Three Nodes Ahead



```
while (p){
    pf(p->next->next->next);
    work(p->data);
    p = p->next;
}
```

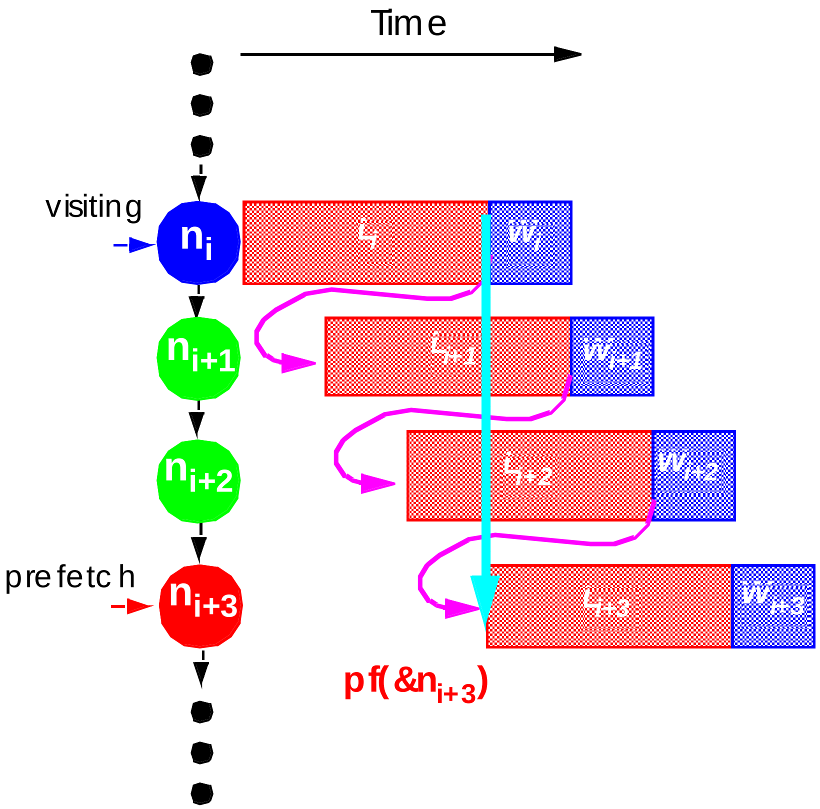
pf(p_i->next->next->next)

computation rate does not improve (still = 1/L)!

Pointer-Chasing Problem:

- any scheme which follows the pointer chain is limited to a rate of 1/L

Our Goal: Fully Hide Latency



```
while (p){
    pf(&n_{i+3});
    work(p->data);
    p = p->next;
}
```

- achieves the fastest possible computation rate of 1/W

Overview

- Challenges in Prefetching Recursive Data Structures
- Three Prefetching Algorithms
    - Greedy Prefetching
    - History-Pointer Prefetching
    - Data-Linearization Prefetching
- Experimental Results
- Conclusions

Pointer-Chasing Problem

Key:

- n_i needs to know $\&n_{i+d}$ without referencing the d-1 intermediate nodes

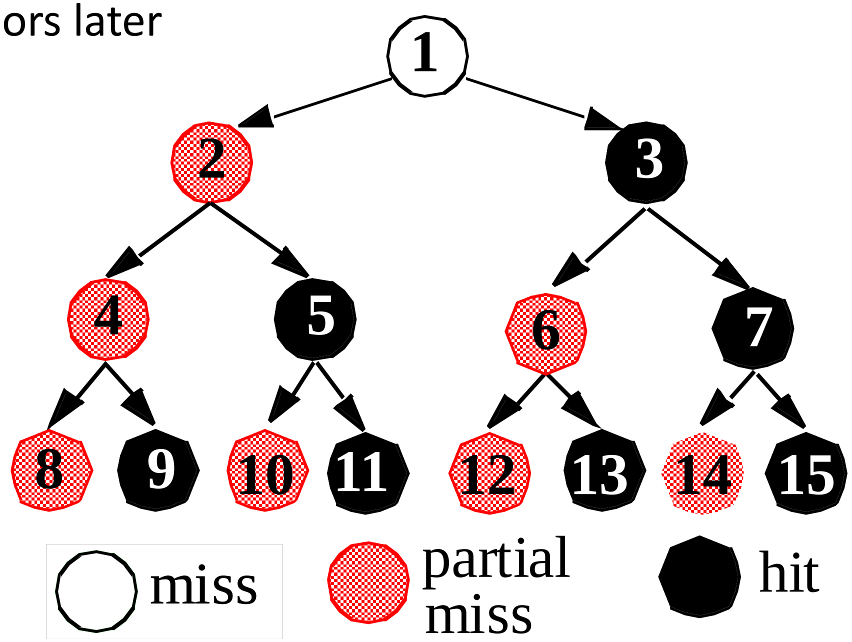
Our proposals:

- use *existing* pointer(s) in n_i to approximate $\&n_{i+d}$
  - Greedy Prefetching
- add *new* pointer(s) to n_i to approximate $\&n_{i+d}$
  - History-Pointer Prefetching
- compute $\&n_{i+d}$ *directly* from $\&n_i$ (no ptr deref)
  - History-Pointer Prefetching

Greedy Prefetching

- Prefetch all neighboring nodes (simplified definition)
  - only one will be followed by the immediate control flow
  - hopefully, we will visit other neighbors later

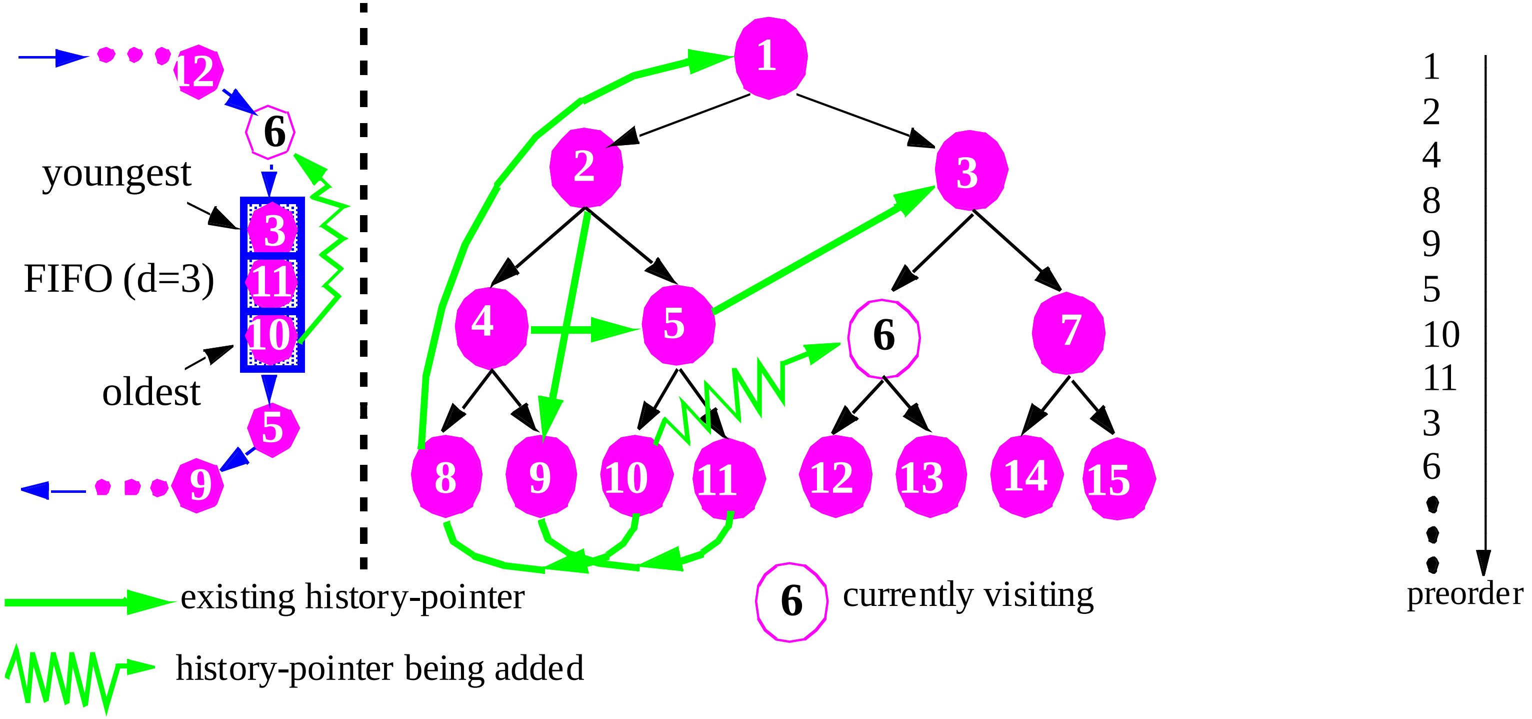
```
preorder(treeNode * t){
  if (t != NULL){
    pf(t->left);
    pf(t->right);
    process(t->data);
    preorder(t->left);
    preorder(t->right);
  }
}
```



- Reasonably effective in practice
- However, little control over the prefetching distance

History-Pointer Prefetching

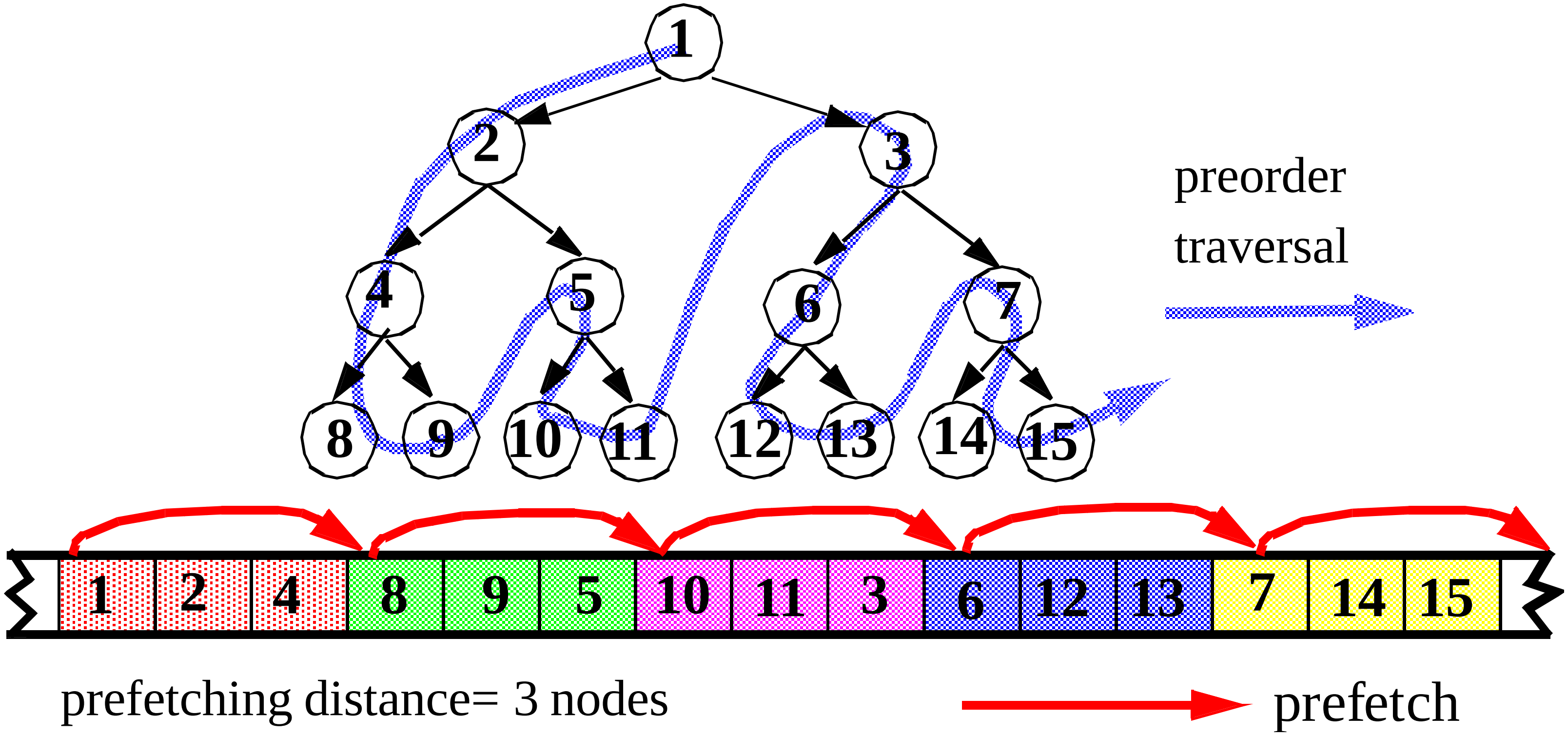
- Add new pointer(s) to each node
  - history-pointers are obtained from some recent traversal



- Trade space & time for better control over prefetching distances

Data-Linearization Prefetching

- No pointer dereferences are required
- Map nodes close in the traversal to contiguous memory



preorder traversal

prefetching distance= 3 nodes

prefetch

Summary of Prefetching Algorithms

	Greedy	History-Pointer	Data-Linearization
Control over Prefetching Distance	little	more precise	more precise
Applicability to Recursive Data Structures	any RDS	revisited; changes only slowly	must have a major traversal order; changes only slowly
Overhead in Preparing Prefetch Addresses	none	space + time	none in practice
Ease of Implementation	relatively straightforward	more difficult	more difficulty

Conclusions

- Propose 3 schemes to overcome the pointer-chasing problem:
  - Greedy Prefetching
  - History-Pointer Prefetching
  - Data-Linearization Prefetching

- Automated greedy prefetching in SUIF
  - improves performance significantly for half of Olden
  - memory feedback can further reduce prefetch overhead

- The other 2 schemes can outperform greedy in some situations

CSC D70: Compiler Optimization Prefetching

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