Reducing Seek Overhead with Application-Directed Prefetching

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Disks are Relatively Slow

	Average Seek Time	Throughput	Whetstone Instr./Sec.
1979	55 ms	0.5 MB/s	0.714 M
2009	8.5 ms	105 MB/s	2,057 M
Improvement	6.5 x	210 x	2,880 x

1979: PDP 11/55 with
an RL02 10MB disk
2009: Core 2 with a Seagate
7200.11 500GB disk

Work Arounds

- Buffer cache – Avoid redoing reads
- Write batching – Avoid redoing writes
- Disk scheduling – Reduce (expensive) seeks
- Readahead – Overlap disk & CPU time

Readahead

- Generally applies to sequential workloads
  - Harsh penalties for mispredicting accesses
  - Hard to predict nonsequential access patterns
- Some workloads are nonsequential
  - Databases
  - Image / Video processing
  - Scientific workloads: simulations, experimental data, etc.

Nonsequential Access

- Why so slow?
  - Seek costs
- Possible solutions
  - More RAM
  - More spindles
  - Disk scheduling
- Why are nonsequential access patterns often scheduled poorly?
  - Painful to get right

Example – Getting it Wrong

- Programmer will access nonsequential dataset

- Prefetch it

  fadvise(fd, data_start, data_size, WILLNEED)

- Now it's slower
  - Maybe prefetching evicted other useful data
  - Maybe the dataset is larger than the cache size

Libprefetch

- User space library
- Provides new prefetching interface
  - Application-directed prefetching
- Manages details of prefetching
- Up to 20x improvement
  - Real applications (GIMP, SQLite)
  - Small modifications (< 1,000 lines per app)

Libprefetch Contributions

- Microbenchmarks – Quantitatively understand problem
- Interface – Convenient interface to provide access information
- Kernel – Some changes needed
- Contention – Share resources

Outline

- Related work
- Microbenchmarks
- Libprefetch interface
- Results

Prefetching

- Determining future accesses
  - Historic access patterns
  - Static analysis
  - Speculative execution
  - Application-directed

- Using future accesses to influence I/O

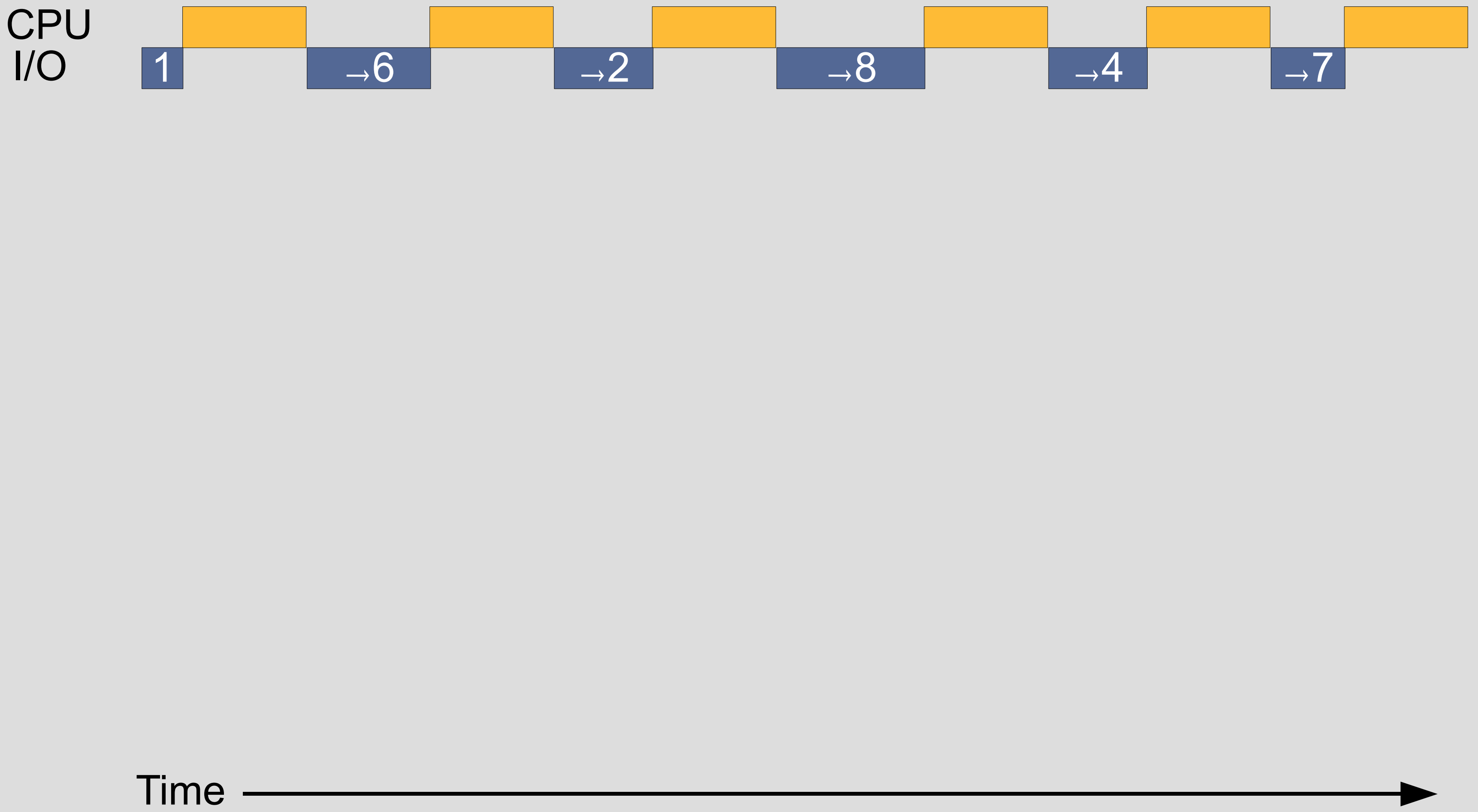
Application-Directed Prefetching

- Patterson (Tip 1995), Cao (ACFS 1996)
- Roughly doubled performance
- Tight memory constraints
  - Little reordering of disk requests
- More in paper

Prefetching

Access pattern: 1, 6, 2, 8, 4, 7

No prefetching



Prefetching

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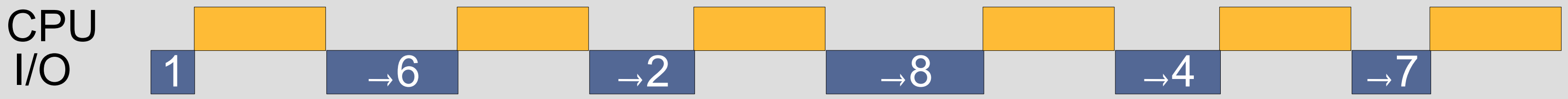
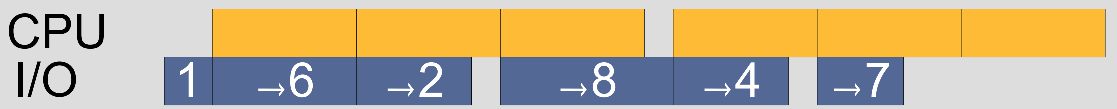


Traditional prefetching – Overlap I/O & CPU



Prefetching

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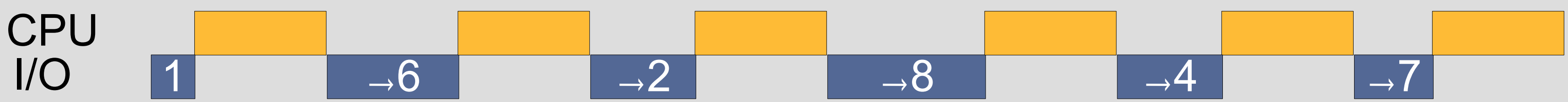

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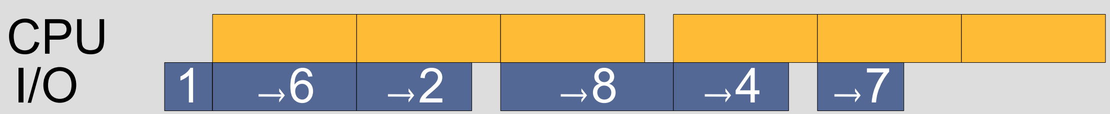
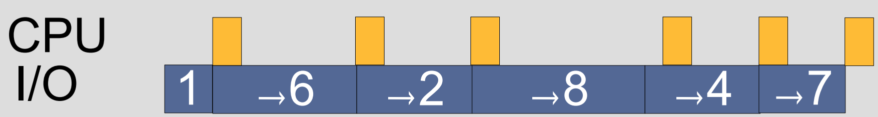
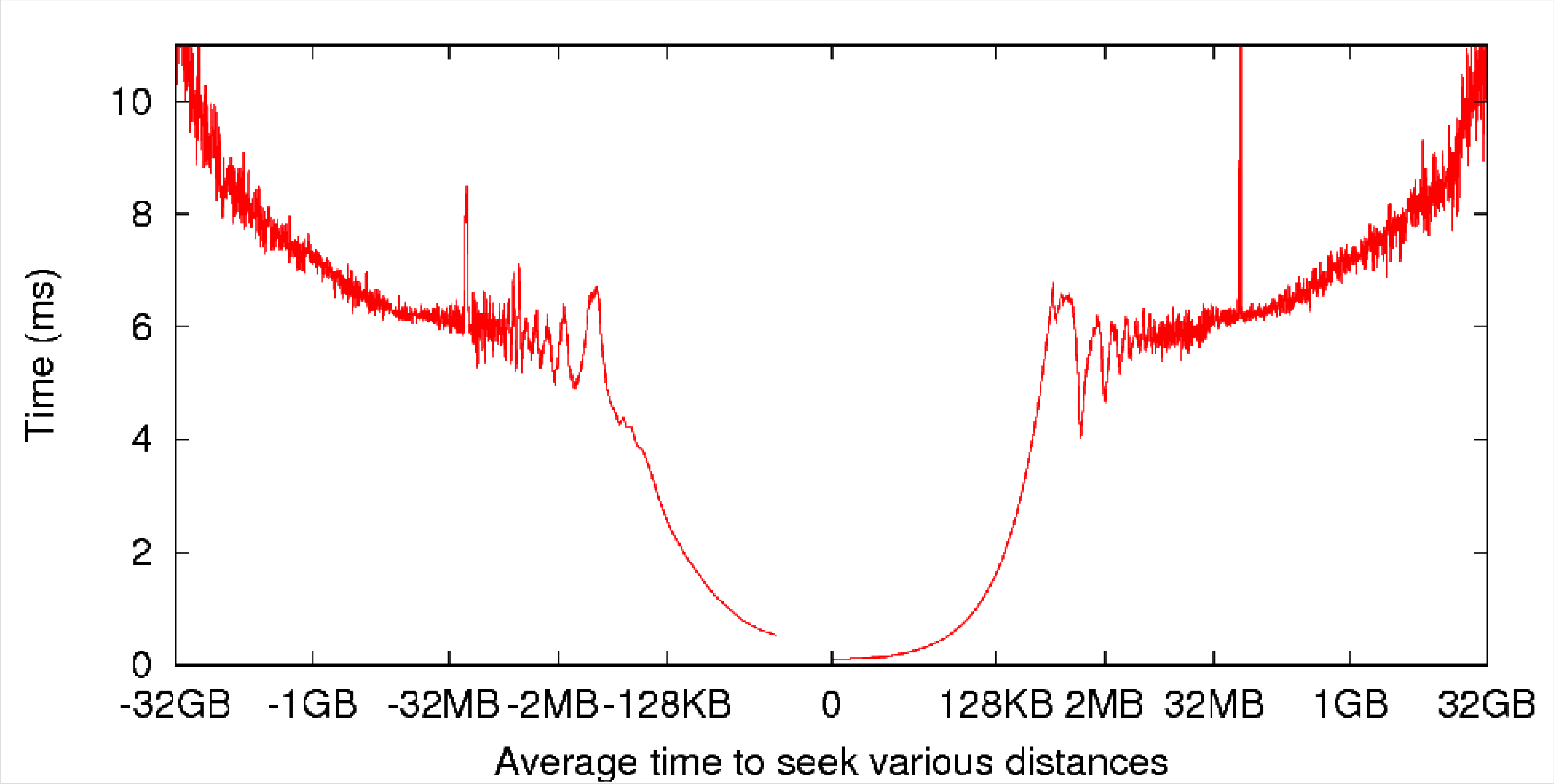


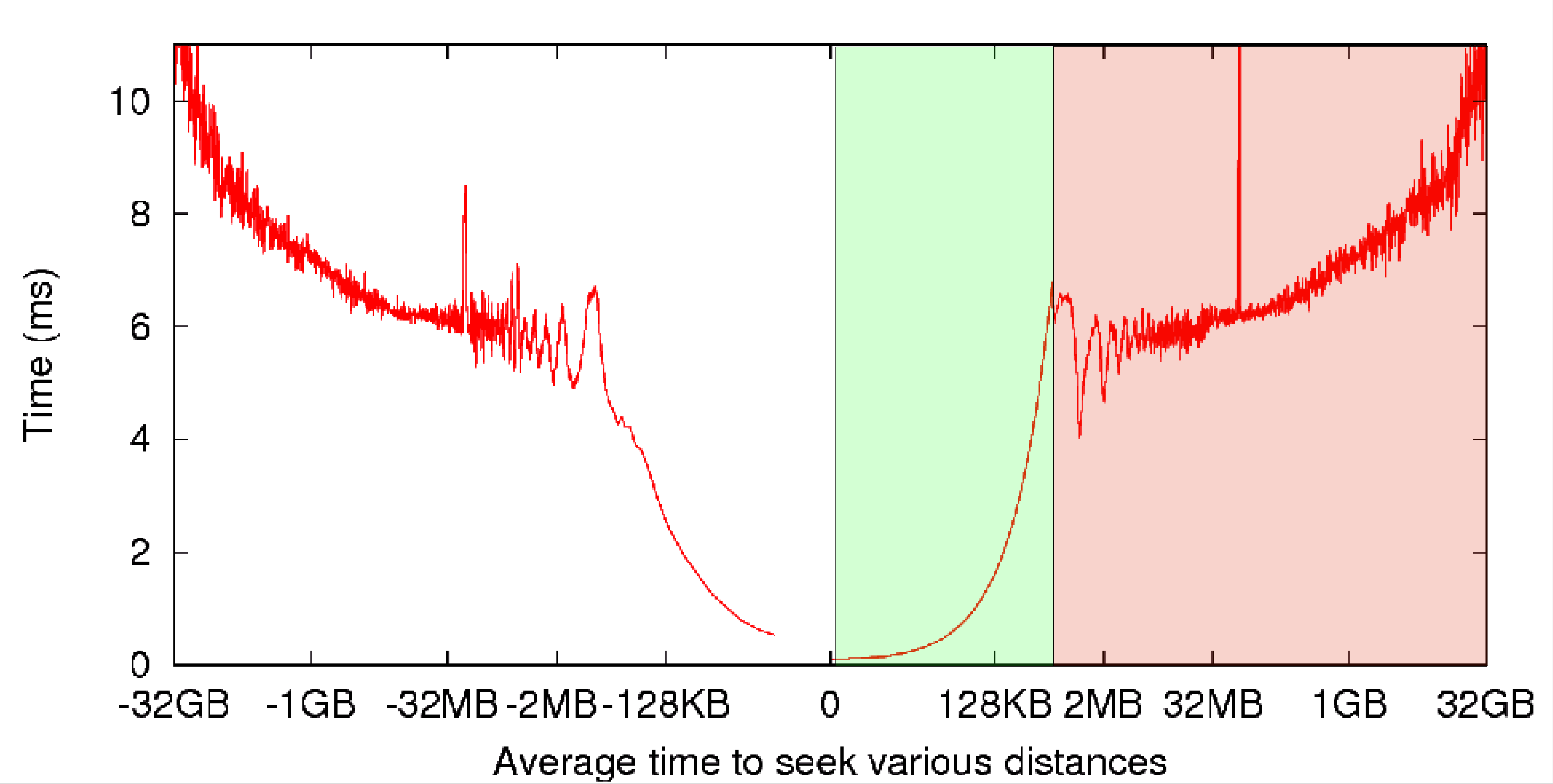
Traditional prefetching – Fast CPU



Seek Performance



Seek Performance

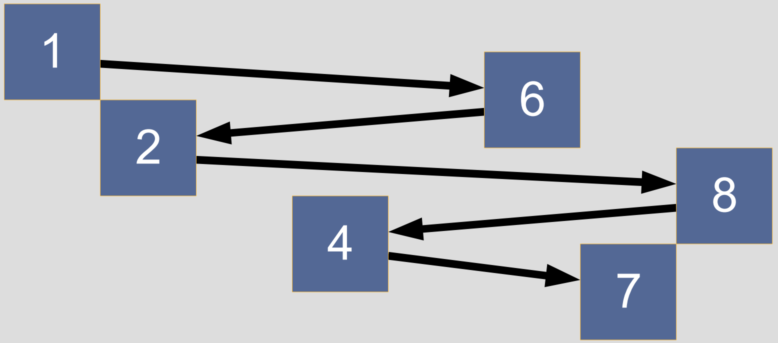


Expensive Seeks

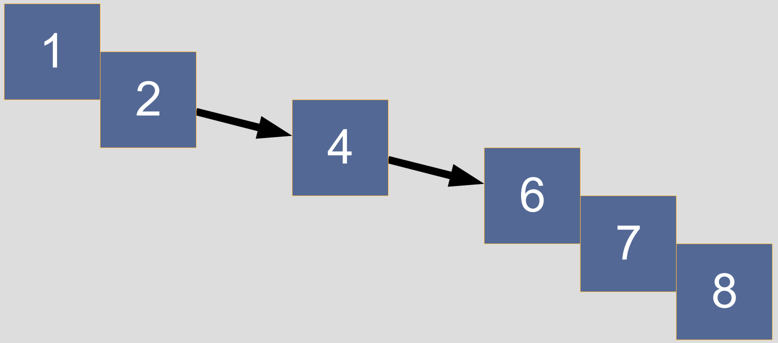
- Minimizing expensive seeks with disk scheduling – reordering

Access pattern: 1, 6, 2, 8, 4, 7

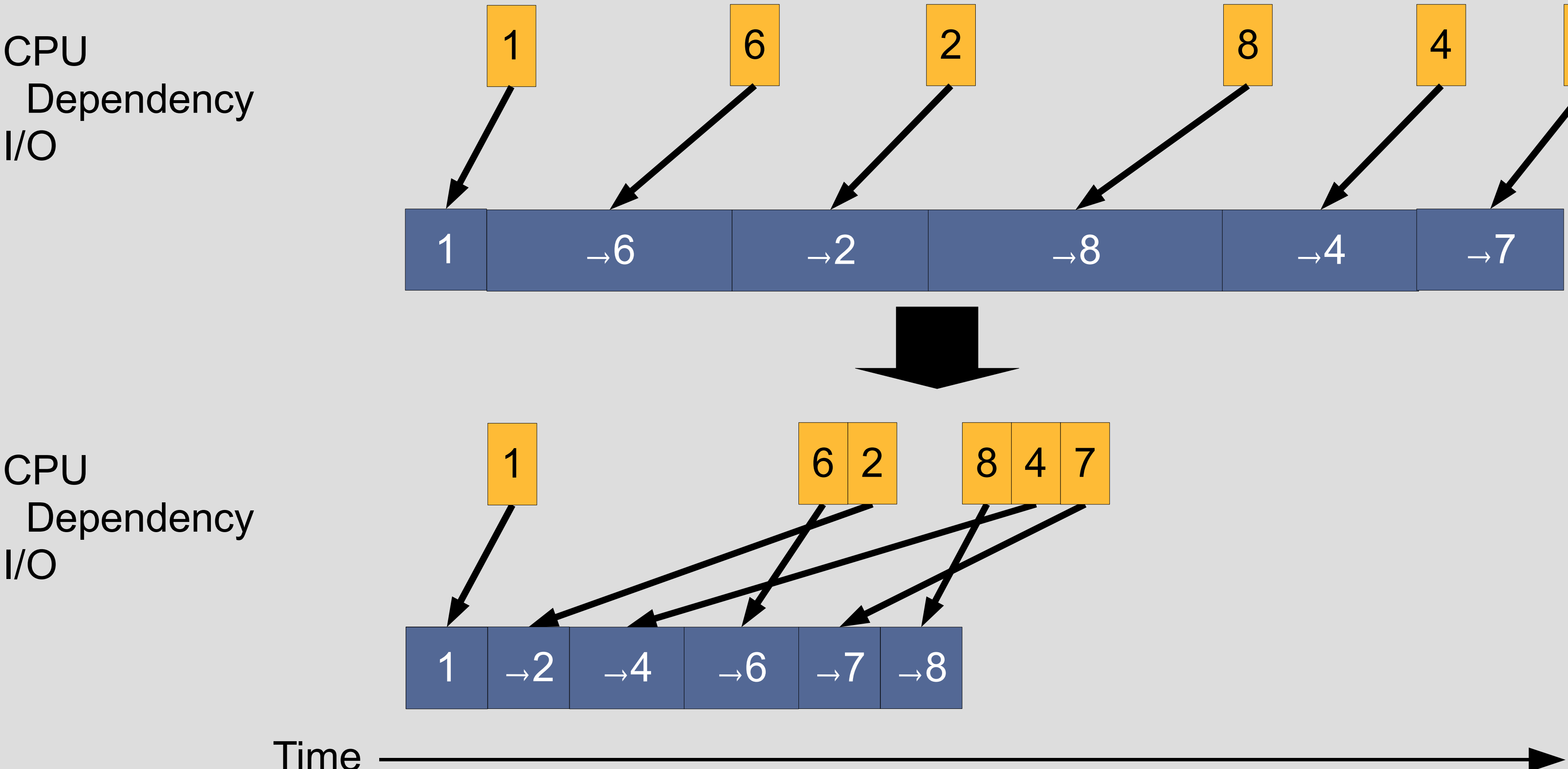
In order:



Reorder:



Reordering

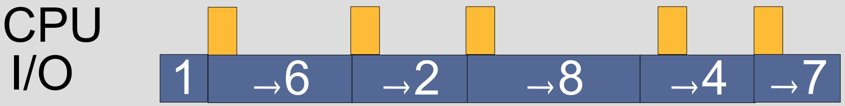


- Must buffer out of order requests
- Reordering limited by buffer space

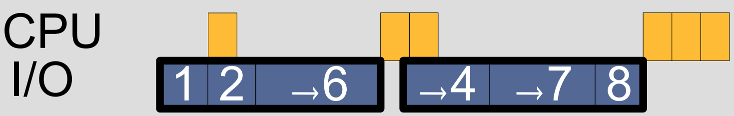
Reorder Prefetching

Access pattern: 1, 6, 2, 8, 4, 7

Traditional prefetching – Fast CPU



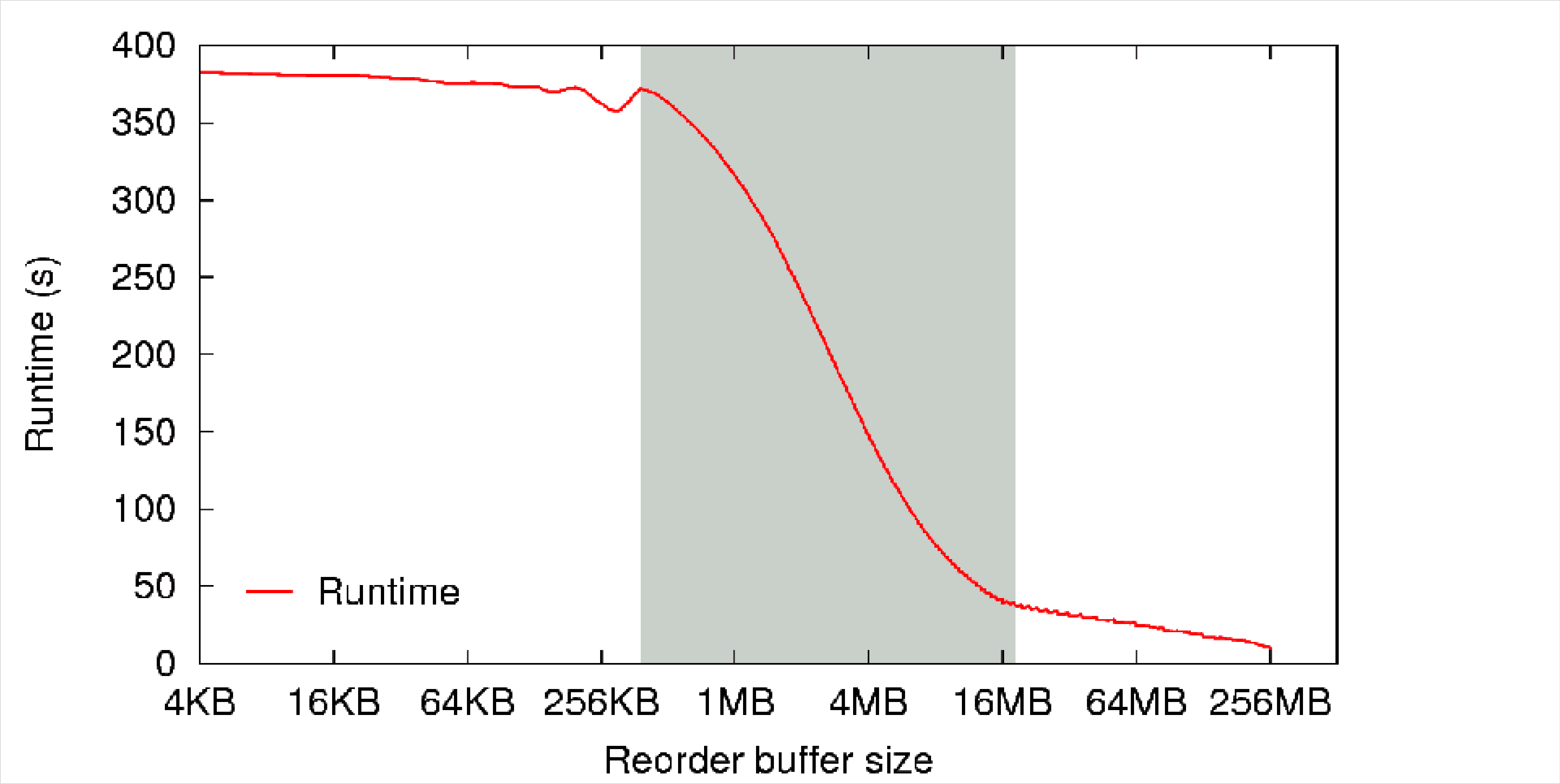
Reorder prefetching – Buffer size = 3



Reorder prefetching – Buffer size = 6

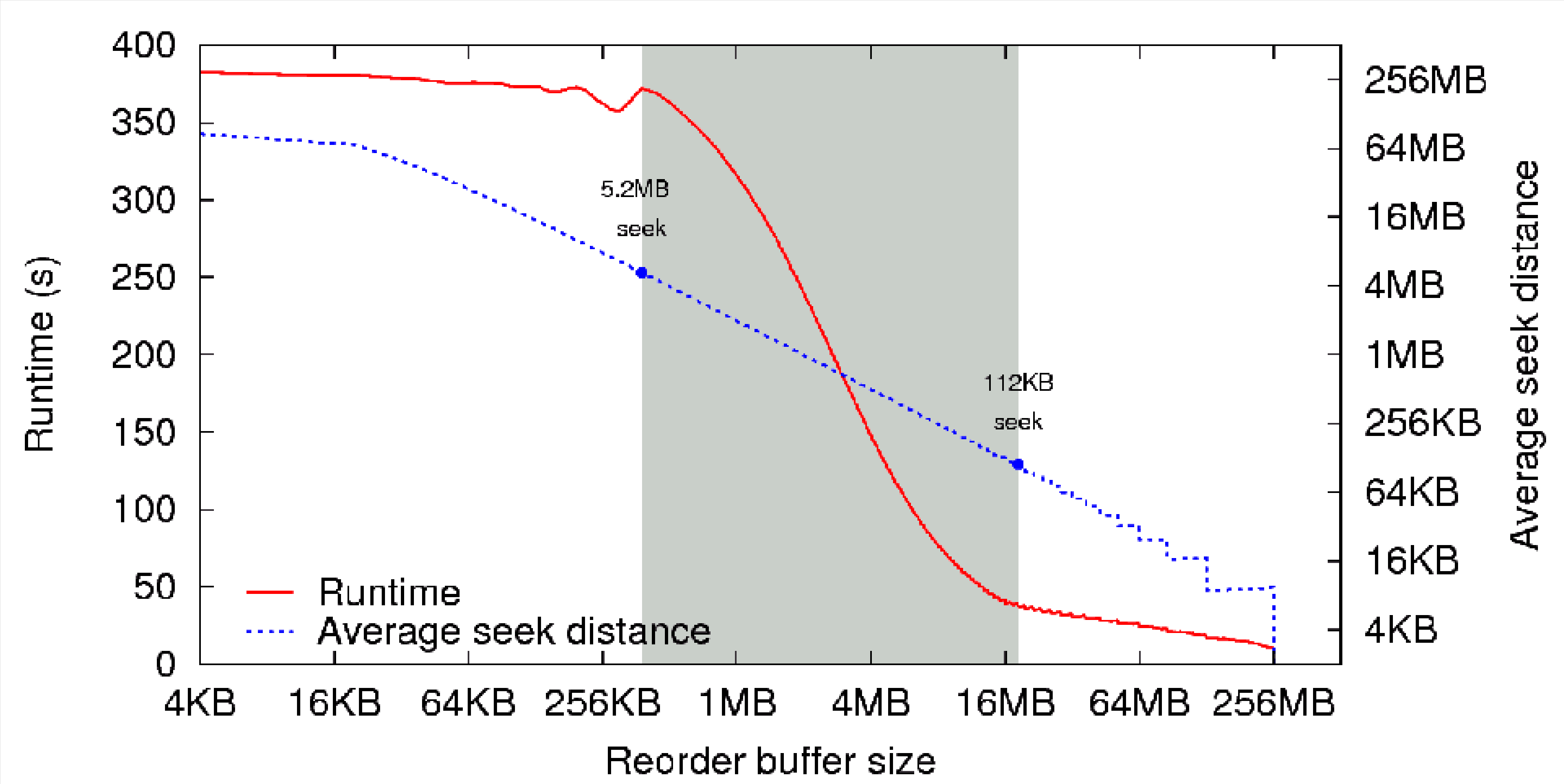
Time →

Buffer Size



Random access to a 256MB file with varying amounts of reordering allowed

Buffer Size



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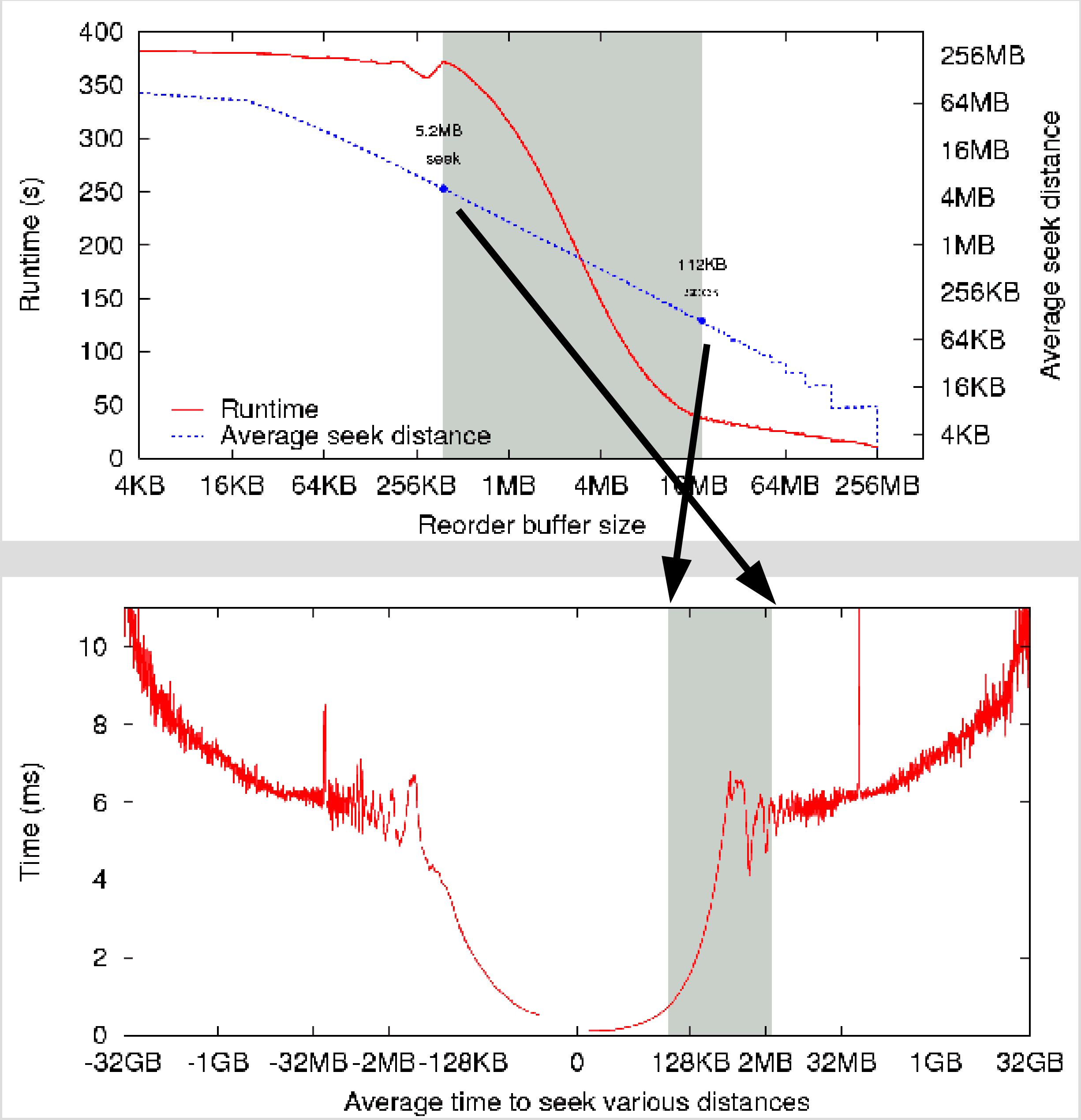
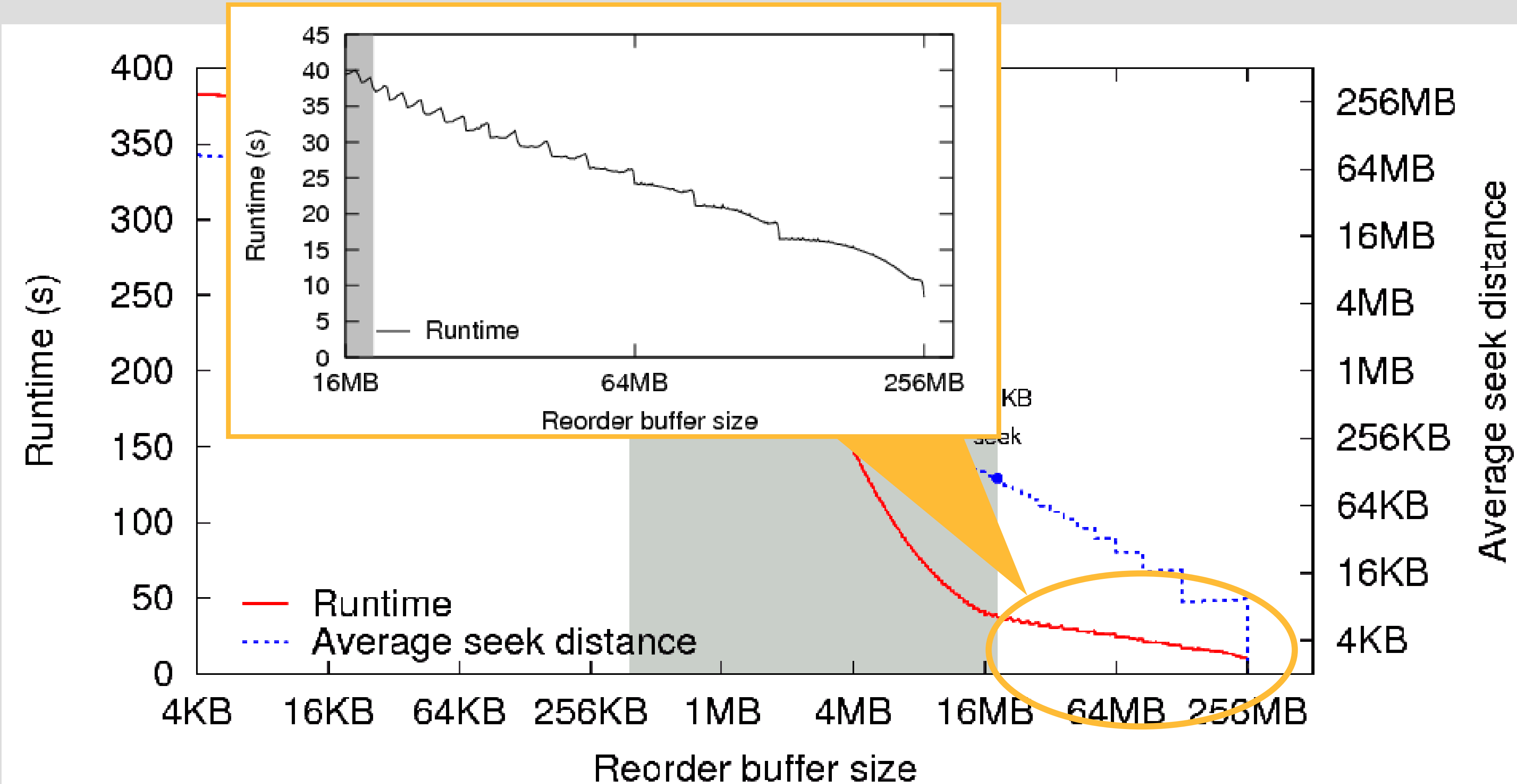

Runtime (s)
400
350
300
250
200
150
100
50
0
4KB
16KB
64KB
256KB
1MB
4MB
16MB
64MB
256MB
Reorder buffer size
256MB
64MB
16MB
4MB
1MB
256KB
64KB
16KB
4KB
Average seek distance
5.2MB
seek
112KB
Runtime
Average seek distance
Time (ms)
10
8
6
4
2
0
-32GB
-1GB
-32MB
-2MB
-128KB
0
128KB
2MB
32MB
1GB
32GB
Average time to seek various distances

Buffer Size



Random access to a 256MB file with varying amounts of reordering allowed

Buffer Size

- Buffer size important to performance
  - Too low: not using all capability, lower performance
  - Too high: evict useful data, performance goes down
- Start with all free and buffer cache memory
  - Libprefetch uses /proc to find free memory
- Change memory target with usage

More microbenchmarks

- Request size
  - Large requests vs. small requests
- Platter location
  - Start of disk vs. end of disk
- Infill
  - Reading extra data to eliminate small seeks

Libprefetch algorithm

- Application-directed prefetching for deep, accurate access lists
- Use as much memory as possible to maximize reordering
- Reorder requests to minimize large seeks

Interface Outline

- List of access entries
- Callback
  - Supply access list incrementally
  - Non-invasive to existing applications

Example

```
c = register_client(callback, NULL);
```

File A

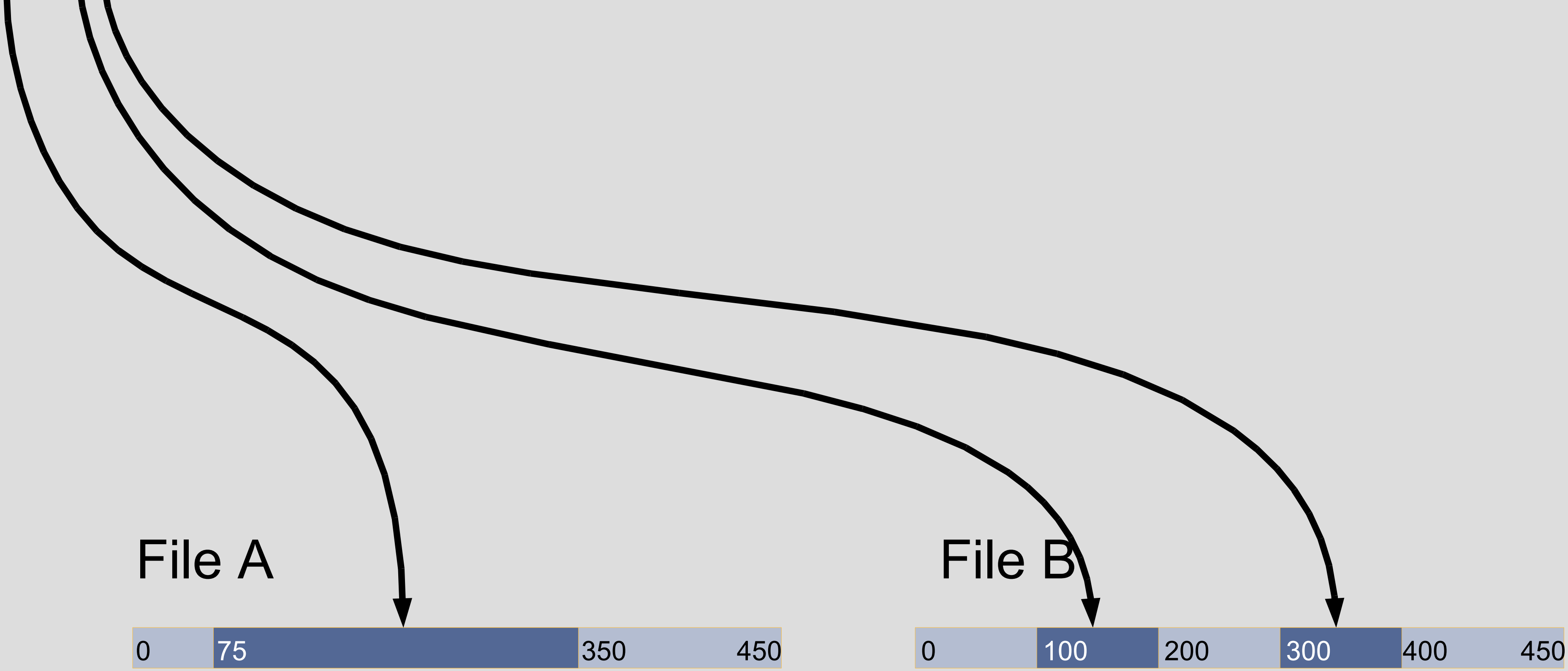
0	450

File B

0	450

Example

```
c = register_client(callback, NULL);
r1 = register_region(c, A, 75, 350);
r2 = register_region(c, B, 100, 200);
r3 = register_region(c, B, 300, 400);
```



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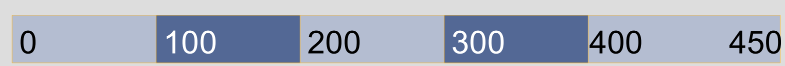
a_list = { {A, 100, 1}, ... {B, 150, 0}, ... {A, 200, 1} };
n = request_prefetching(c, a_list, 3, PF_SET | PF_DONE);
```

File A

File B



Example

c = **register_client(**

r1 = **register_regio**

r2 = **register_region**

r3 = **register_region**(, B, 300, 400);

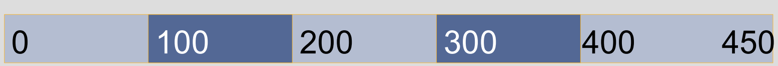
Access list entry:
file descriptor,
file offset,
marked flag

a_list = { {A, 100, 1}, ... {B, 150, 0}, ... {A, 200, 1} };

n = **request_prefetching**(c, a_list, 3, PF_SET | PF_DONE);

File A

File B



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n = request_prefetching(c, a_list, 3, PF_SET | PF_DONE);
```
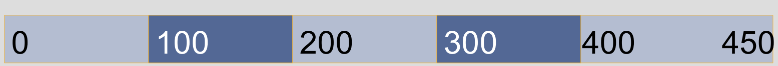

Flags:
- append,
- clear,
- complete

File A

File B



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n = request_prefetching(c, a_list, 3, PF_SET | PF_DONE);
```

Accepted entries
“short” = full

File A

File B

Example

c = **register_client**(callback, NULL);

r1 = **register_region**(c, A, 75, 350);

r2 = **register_region**(c, B, 100, 200);

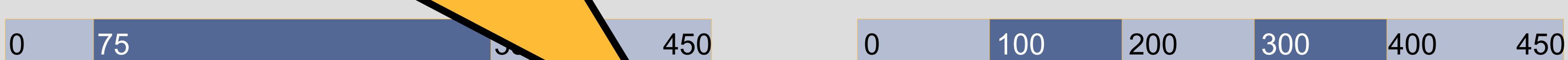
r3 = **register_region**(c, B, 300, 400);

a_list = { {A, 100, 1}, ... {B, 150, 0}, ... {A, 200, 1} };

n = **request_prefetching**(c, a_list, 3, PF_SET | PF_DONE);

fadvise(A, 100, WILL_NEED)
…
fadvise(B, 150, WILL_NEED)
…
fadvise(A, 200, WILL_NEED)

File B



libprefetch_a_list = {{A, 100, 1}, ... {B, 150, 0}, ... {A, 200, 1}};

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a_list = { {A, 100, 1}, ... {B, 150, 0}, ... {A, 200, 1} };
n = request_prefetching(c, a_list, 3, PF_SET | PF_DONE);

pread(A, ..., 100);
```
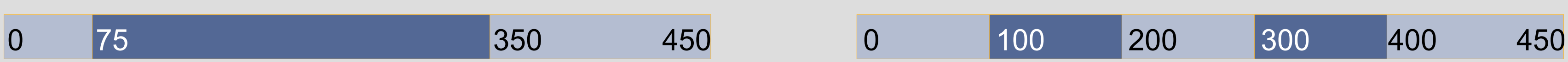

File A

File B



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pread(A, ..., 100);
```

Check access list
Check in memory
fincore(A, 100, ...)

File A


```
libprefetch_a_list = {{A, 100, 1}, ... {B, 150, 0}, ... {A, 200, 1}};
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a_list = { {A, 100, 1}, ... {B, 150, 0}, ... {A, 200, 1} };

n = **request_prefetching**(c, a_list, 3, PF_SET | PF_DONE);

Access list doesn't match. Callback into application to update it.

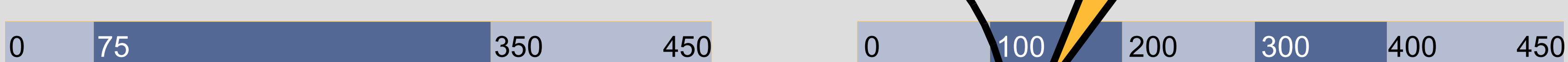
pread(A, ..., 100);

...

~~**pread**(B, ..., 350);~~

File A

File B



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pread(A, ..., 100);
...
```

```
void callback(void* arg, int markedFD, loff_t markedOffset,
              int requestedFD, loff_t requestedOffset);
```

libprefetch_a_list = {{A, 100, 1}, ... {B, 150, 0}, ... {A, 200, 1}};

Example

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a_list = { {A, 100, 1}, ... {B, 150, 0}, ... {A, 200, 1} };
n = request_prefetching(c, a_list, 3, PF_SET | PF_DONE);

pread(A, ..., 100);
...
    void callback(NULL, A, 100, B, 350) {
        a_list = compute_new_alist(B, 350);
        n = request_prefetching(c, a_list, 2, PF_SET | PF_DONE);
    }
```

libprefetch_a_list = {{A, 100, 1}, ... {B, 150, 0}, ... {A, 200, 1}};

Example

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r1 = register_region(c, A, 75, 350);
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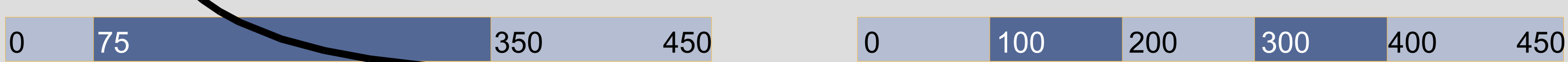

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n = **request_prefetching**(c, a_list, 3, PF_SET | PF_DONE);

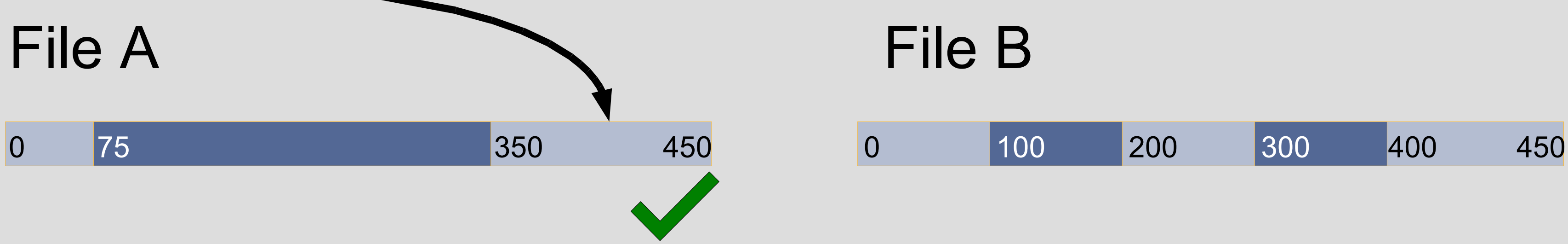
pread(A, ..., 100);

...

pread(B, ..., 350);

...

~~**pread**(A, ..., 400);~~



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a_list = { {A, 100, 1}, ... {B, 150, 0}, ... {A, 200, 1} };

n = **request_prefetching**(c, a_list, 3, PF_SET | PF_DONE);

pread(A, ..., 100);

...

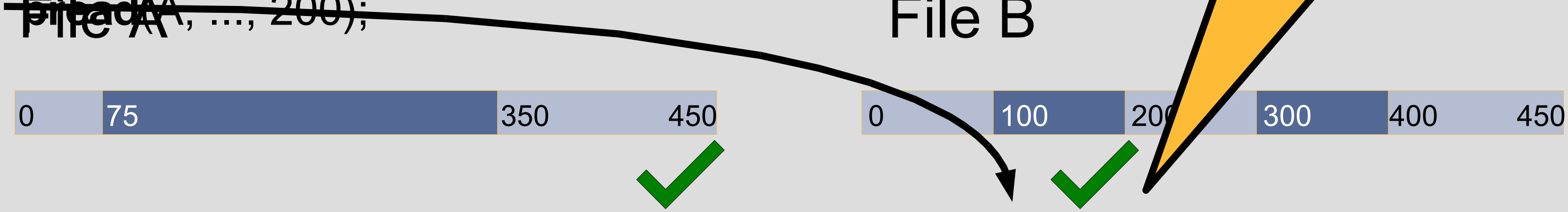
pread(B, ..., 350);

...

pread(A, ..., 400);

~~**pread**(A, ..., 200);~~

End of access list, callback to get more information.



libprefetch_a_list = {{B, 150, 0}, ... {A, 200, 1}};

Interface Summary

- Access list
  - Simply discloses application's intentions
  - Provided incrementally

- Callback
  - Asks application for more information
  - Easily retrofitted into existing applications
  - Aids in debugging access list information

Libprefetch

- Prefetching library
- A few important kernel modifications
  - fincore() - File page in memory?
  - Modified fadvise() - Fetch/evict file page
- Uses fadvise() to prefetch; manages details
  - When to prefetch
  - How much to prefetch
  - Right order for prefetching

Contention

- Disk scheduling – OS scheduler ok
- Memory for libprefetch behaves like bandwidth in TCP
  - Changes quickly
  - Performs poorly if over subscribed
- Use AIMD to determine memory target
  - Decrease when miss in buffer cache
  - Increase when all prefetched data stays in memory

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Evaluation Methodology

- Pentium 4, 3.2GHz
- 512MB of RAM
- Seagate 7200.11 500GB SATA 3Gb/s
- Silicon Image 3132-2 SATA controller
- Logging over the network

Random Access

- SQLite with TPC-C like dataset:

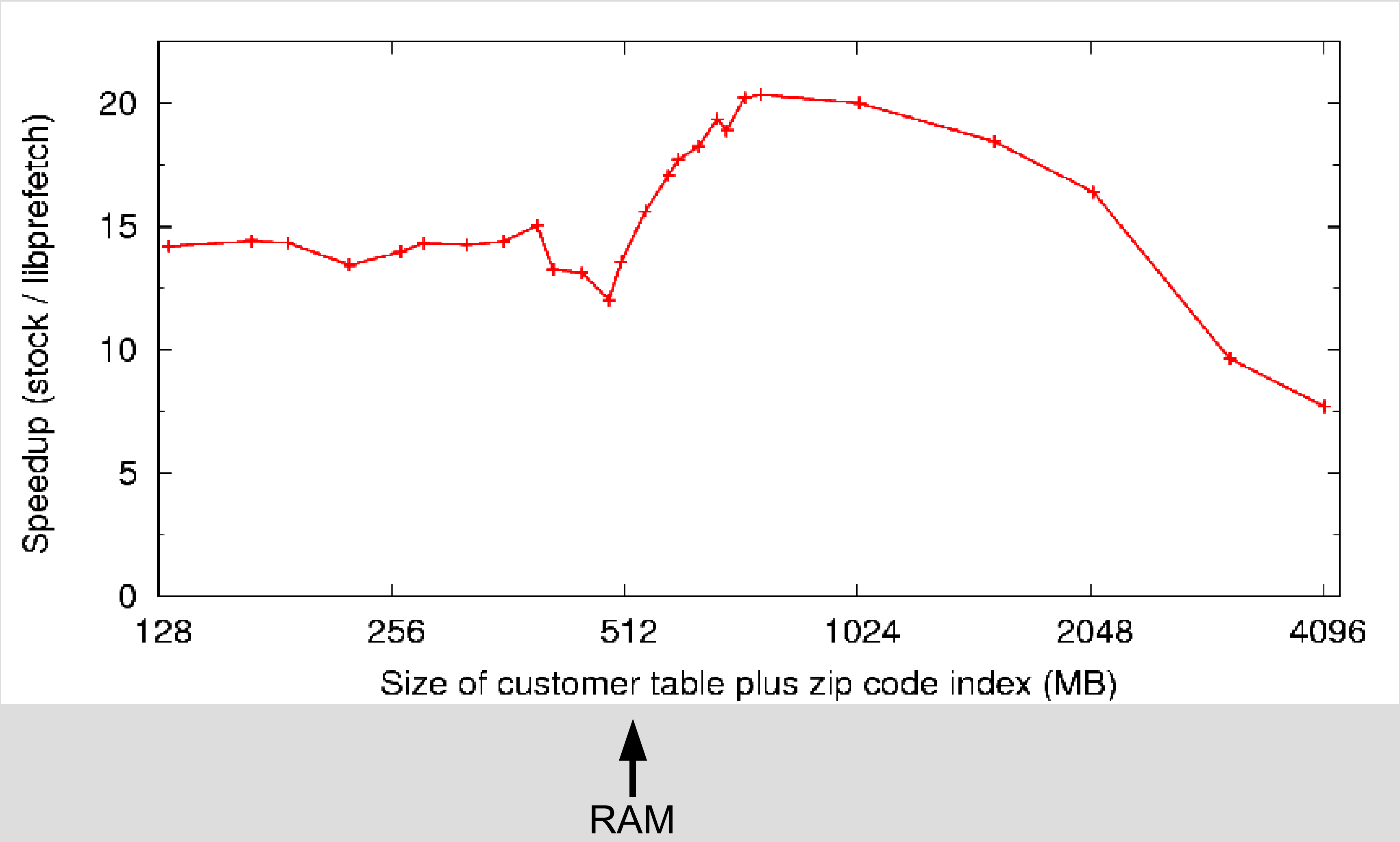
select * from Customer order by Zip_code;

- Secondary key => resulting rows will be randomly located in the dataset

- Total modifications: < 500 lines of code

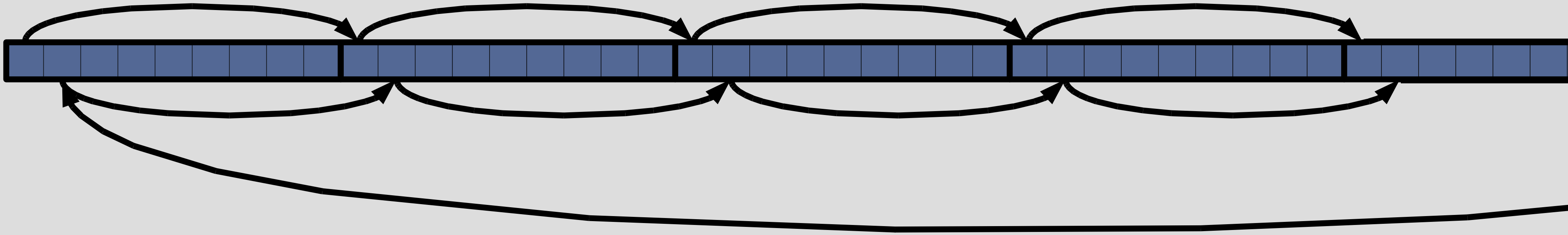
Results: Random

- SQLite secondary key query



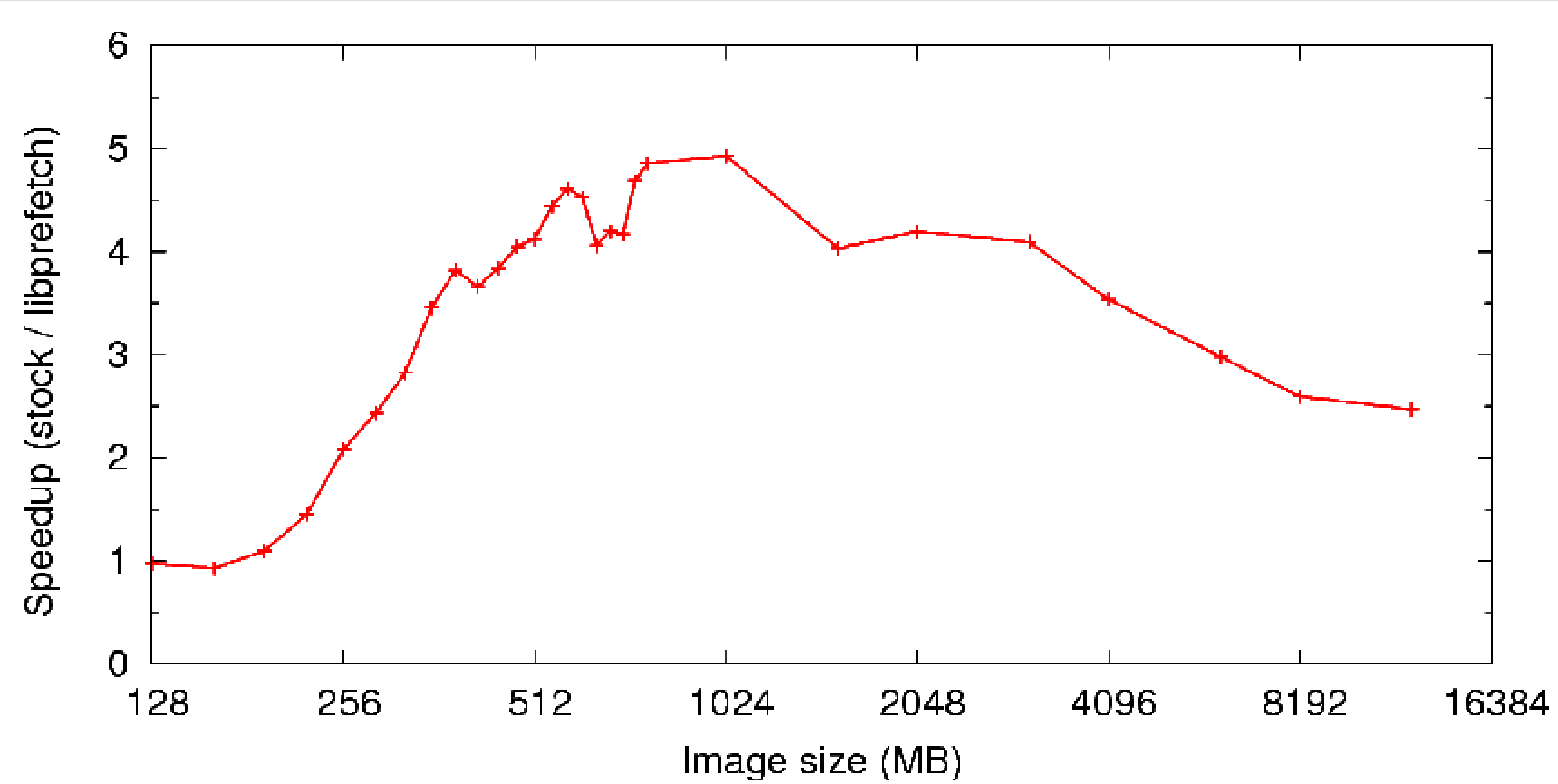
Strided Accesses

- GIMP
  - Array of image tiles
  - Row-major layout accessed in Column-major order
  - Column-major layout accessed in Row-major order
  - Total modifications: 679 lines



Results: Strided

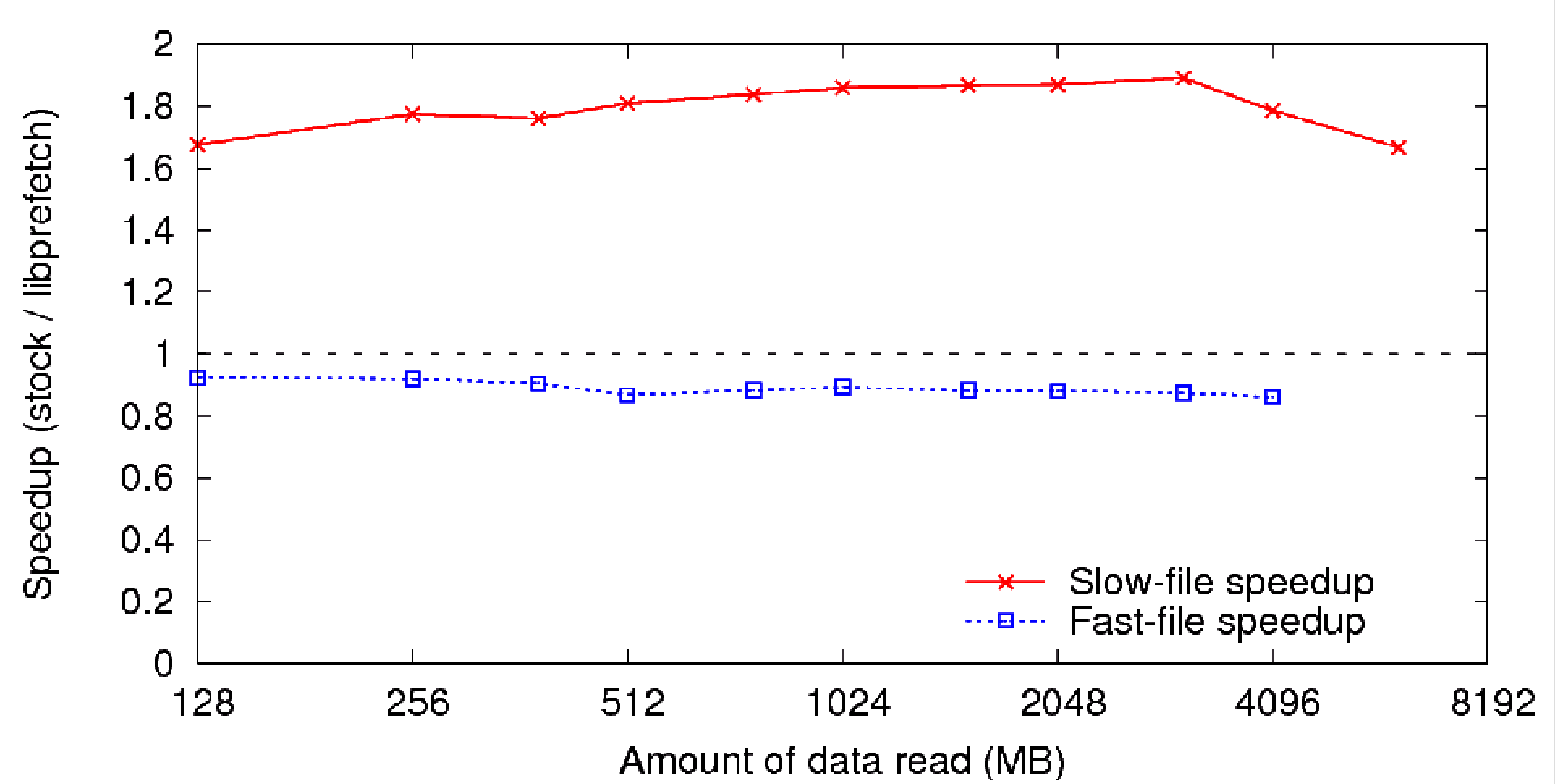
- GIMP blur



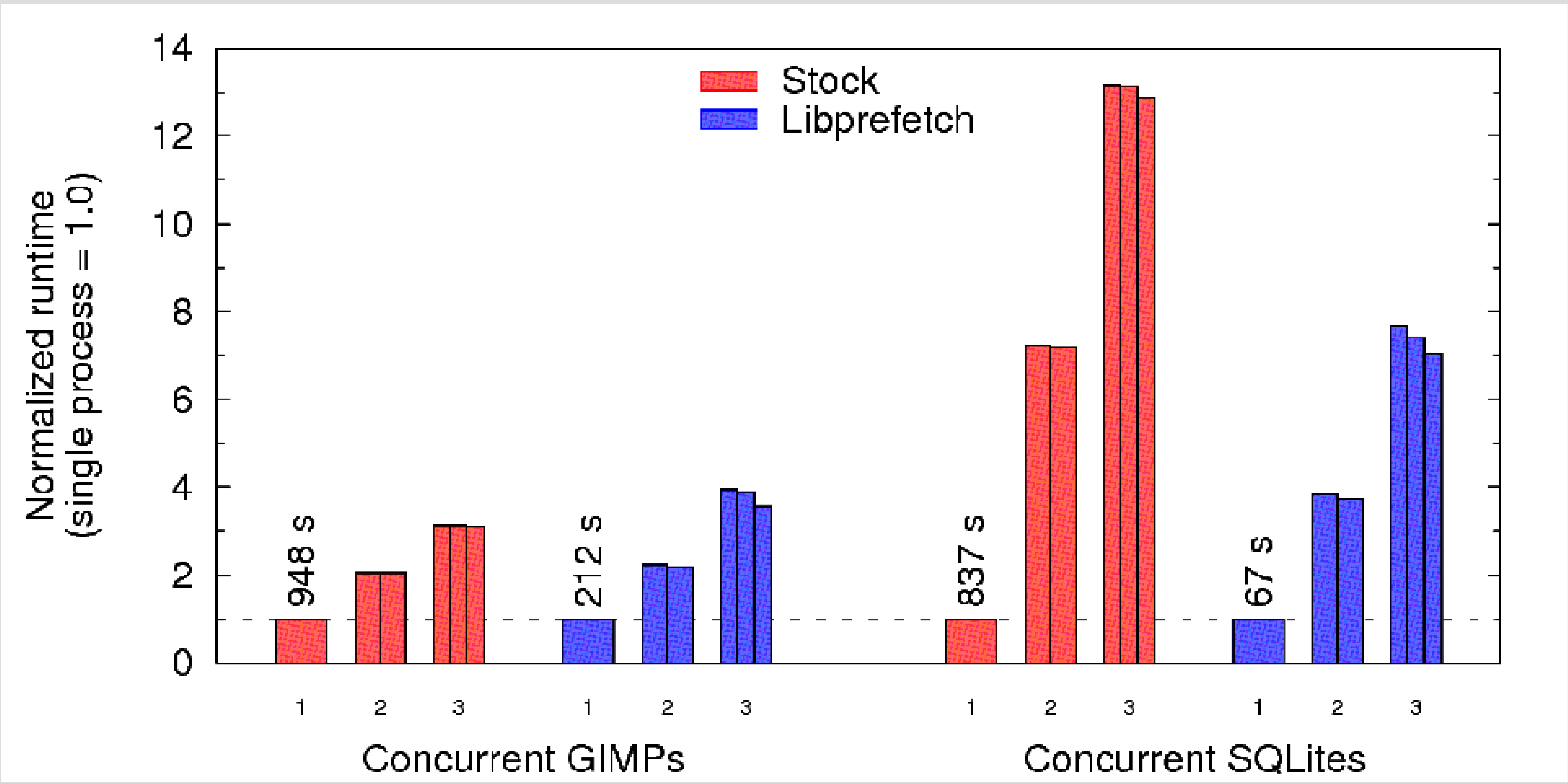
Sequential Access

- Sequentially read a large file
- Libprefetch should do just as well as readahead

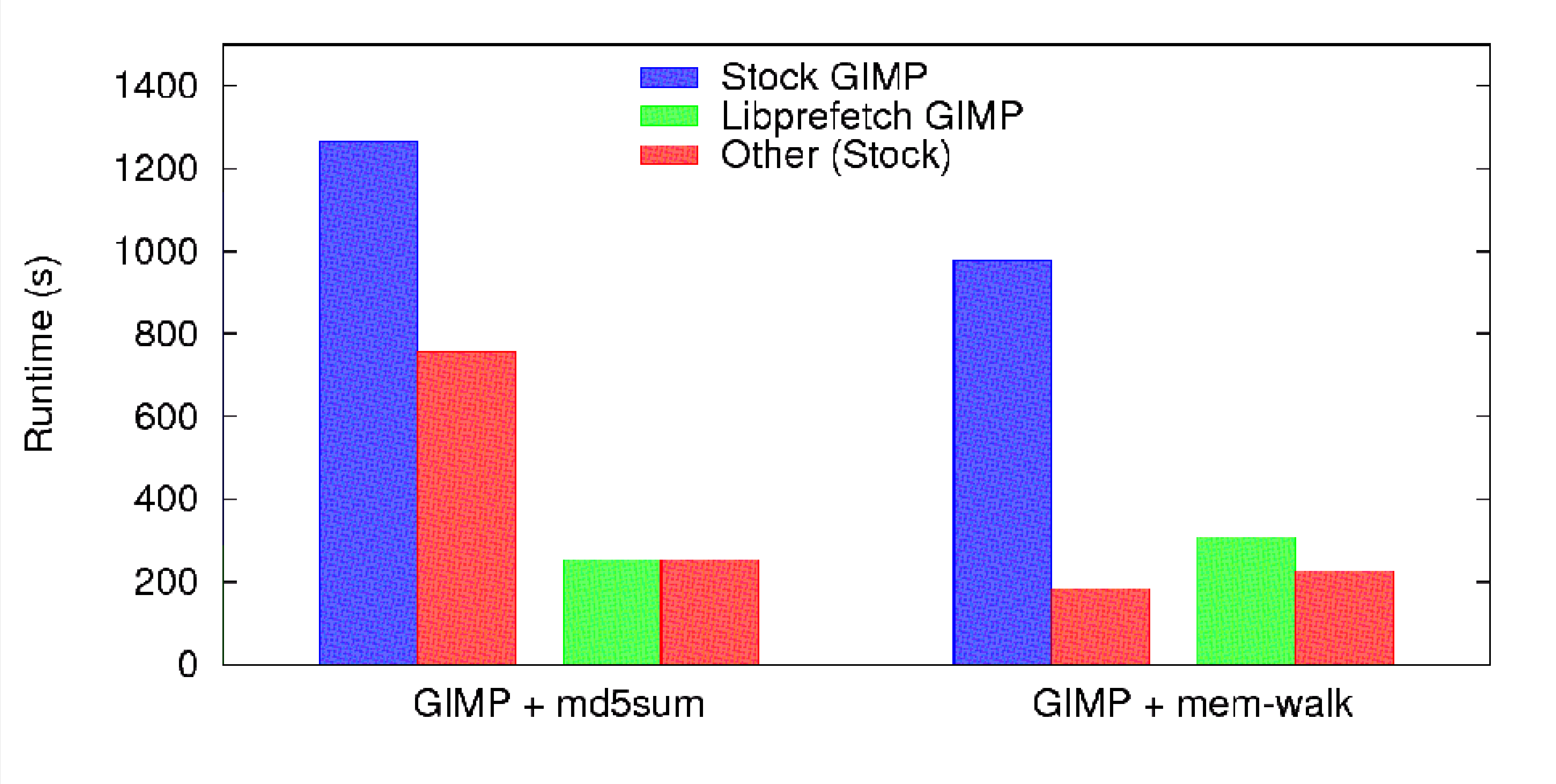
Results: Sequential



Impact of AIMD



Performance with Contention



Conclusion

- A relatively simple library can transform accesses to avoid slow operations
- Microbenchmarks quantitatively show cause of nonsequential slowness
- Interface to easily retrofit applications
- Libprefetch handles kernel and concurrency complications
- Big performance gains (up to 20x) are possible for some workloads

Implementation Sketch

1. Scan access list – find enough entries to fill memory

2. fadvise(DONT_NEED) old entries

3. Sort new entries by file offset

4. fadvise(WILL_NEED) new entries

5. Return to intercepted read