Secondary Storage

Any modern computer system will incorporate (at least) two levels of storage:

<u>**primary storage**</u>**:**	**random access memory (DRAM)**	
typical capacity	4 GB to 32 GB	
cost per GB	$4.00	
typical transfer rate	20,000 MB/sec	
<u>**secondary storage**</u>**:**	**magnetic disk**	**SSD**
typical capacity	500 GB to 8 TB	128GB to 4TB
cost per GB	$0.025	$0.22
typical transfer rate	150 MB/sec	2000 MB/sec

Note: all statistics here were obtained on Oct 22, 2020.

Units of Measurement

Spatial units:

IEC standard

byte (B)	8 bits
kibibyte (KiB)	1024 or 2^{10} bytes
mebibyte (MiB)	1024 kibibytes or 2^{20} bytes
gibibyte (GiB)	1024 mebibytes or 2^{30} bytes

traditional

byte (B)	8 bits
kilobyte (KB)	1024 or 2^{10} bytes
megabyte (MB)	1024 kilobytes or 2^{20} bytes
gigabyte (GB)	1024 megabytes or 2^{30} bytes

alt. industry

byte (B)	8 bits
kilobyte (KB)	1000 or 10^{3} bytes
megabyte (MB)	1000 kilobytes or 10^{6} bytes
gigabyte (GB)	1000 megabytes or 10^{9} bytes

Time units:

picosecond (ps)	one-trillionth (10^{-12}) of a second
nanosecond (ns)	one-billionth (10^{-9}) of a second
microsecond (μs)	one-millionth (10^{-6}) of a second
millisecond (ms)	one-thousandth (10^{-3}) of a second

Primary versus Secondary Storage

While the particular values given earlier are volatile, the relative performances suggested are actually fairly stable over time:

Primary storage:

- costs 100-200 times as much per unit as secondary storage.
- has transfer rates that are perhaps 100-200 times faster

Why do WE care (in a data structures class)?

For many applications

- full data sets are too large to store in memory at once
- data must be first read from secondary storage into memory for processing
- and then results must be written back to secondary storage after processing

Caching Disk Data for Performance

What can a programmer do to improve performance in disk-heavy applications?

- take an idea from the use of memory caches in hardware designs
- create an in-memory (DRAM) data structure to hold recently- and/or frequently-accessed records
- count on *locality of reference* in the application's record retrievals
- strive for the average record fetch to resemble a DRAM access rather than a secondary storage access

We call such a data structure a *buffer pool*.

Locality of Reference

In view of the previous discussion of secondary storage, it makes sense to design programs so that data is read from and written to disk in relatively large chunks… but there is more.

Temporal Locality of Reference

In many cases, if a program accesses one part of a file, there is a high probability that the program will access the same part of the file again in the near future.

Moral: once you've grabbed a chunk, keep it around.

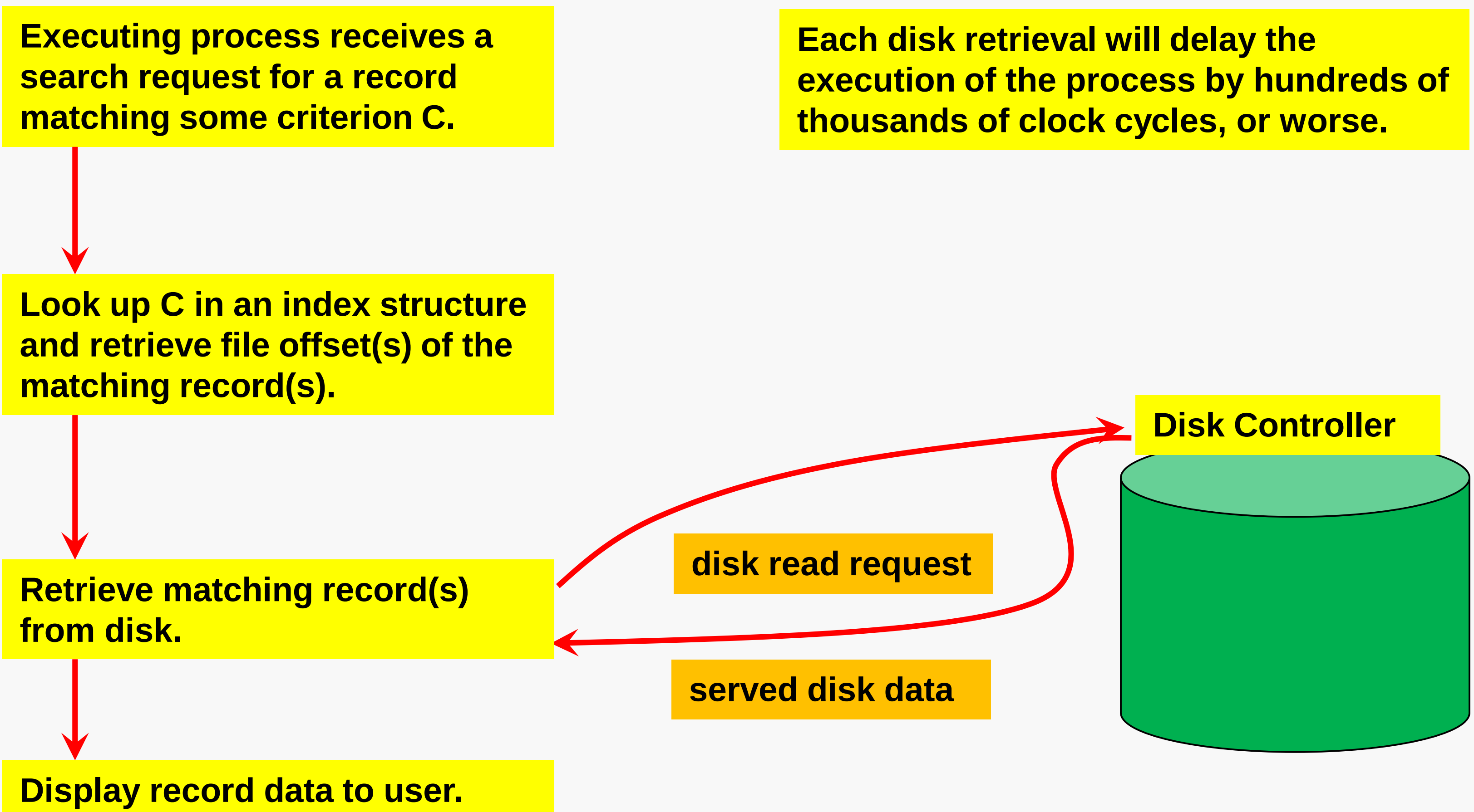
Spatial Locality of Reference

In many cases, if a program accesses one part of a file, there is a high probability that the program will access nearby parts of the file in the near future.

Moral: grab a larger chunk than you immediately need.

Naïve Record Retrieval from Disk

A program that retrieves records from disk in response to search requests would (naively) have interactions like this:



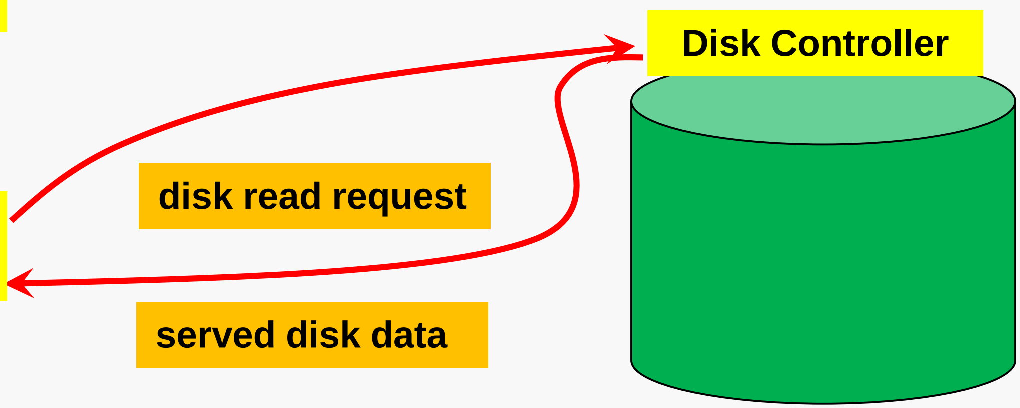
Naïve Record Retrieval from Disk

Not only does this hurt performance when a record is retrieved, we pay the same time cost if that same record is requested again…

Executing process receives a search request for a record matching some criterion C.

Look up C in an index structure and retrieve file offset(s) of the matching record(s).

Retrieve matching record(s) from disk.



Display record data to user.

So, if the searches exhibit temporal locality, this adds insult to injury…

Buffer Pools

buffer pool	a series of buffers (memory locations) used by a program to cache disk data

Basically, the buffer pool is just a collection records, stored in RAM.

When a record is requested, the program first checks to see if the record is in the pool.

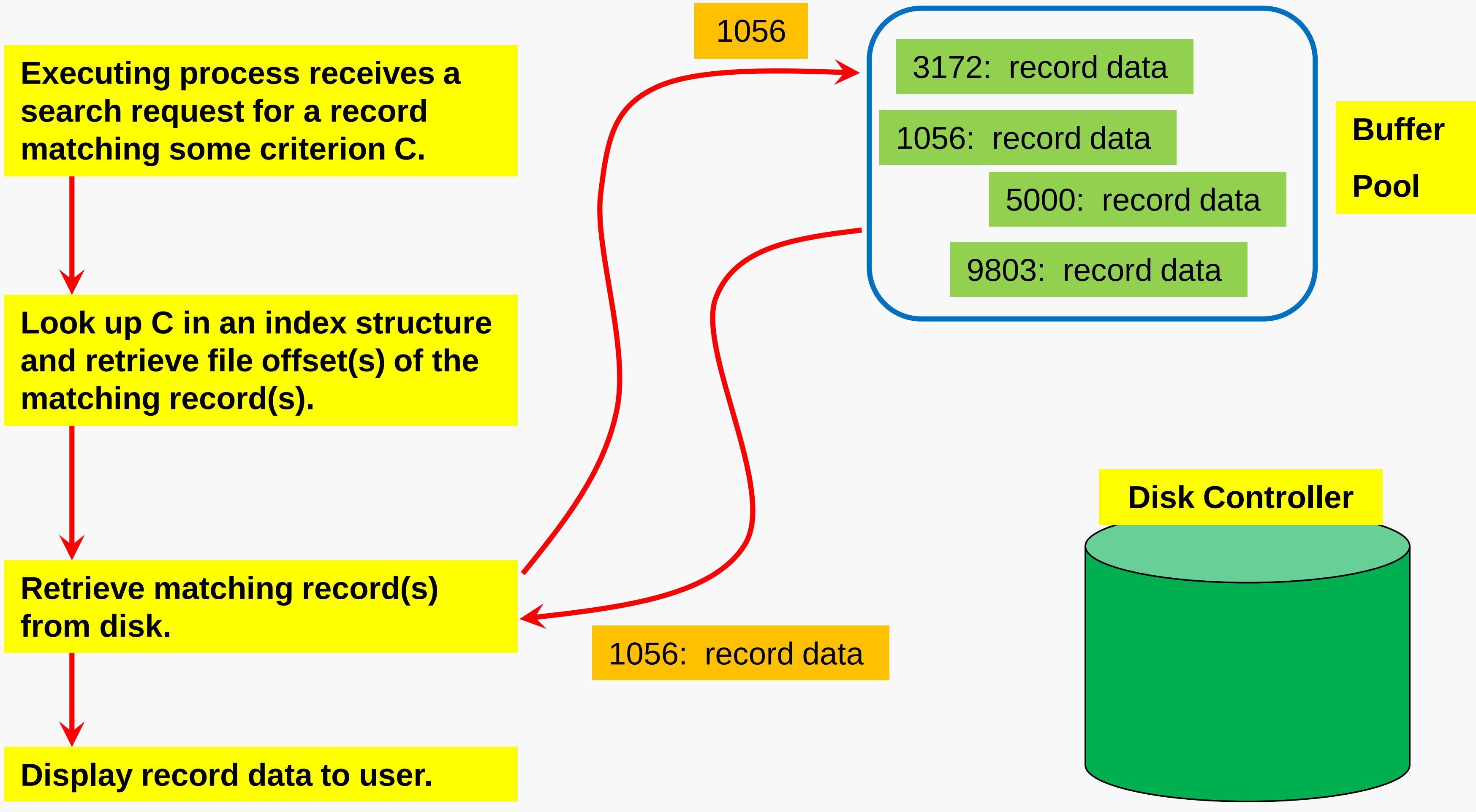
If so, there's no need to go to disk to get the record, and time is saved.

When the program does retrieve a record from disk, the newly-read record is copied into the pool, replacing a currently-stored record if necessary.

Retrieving Records using a Buffer Pool

The interaction of the rest of the process with the disk is now mediated by the pool.

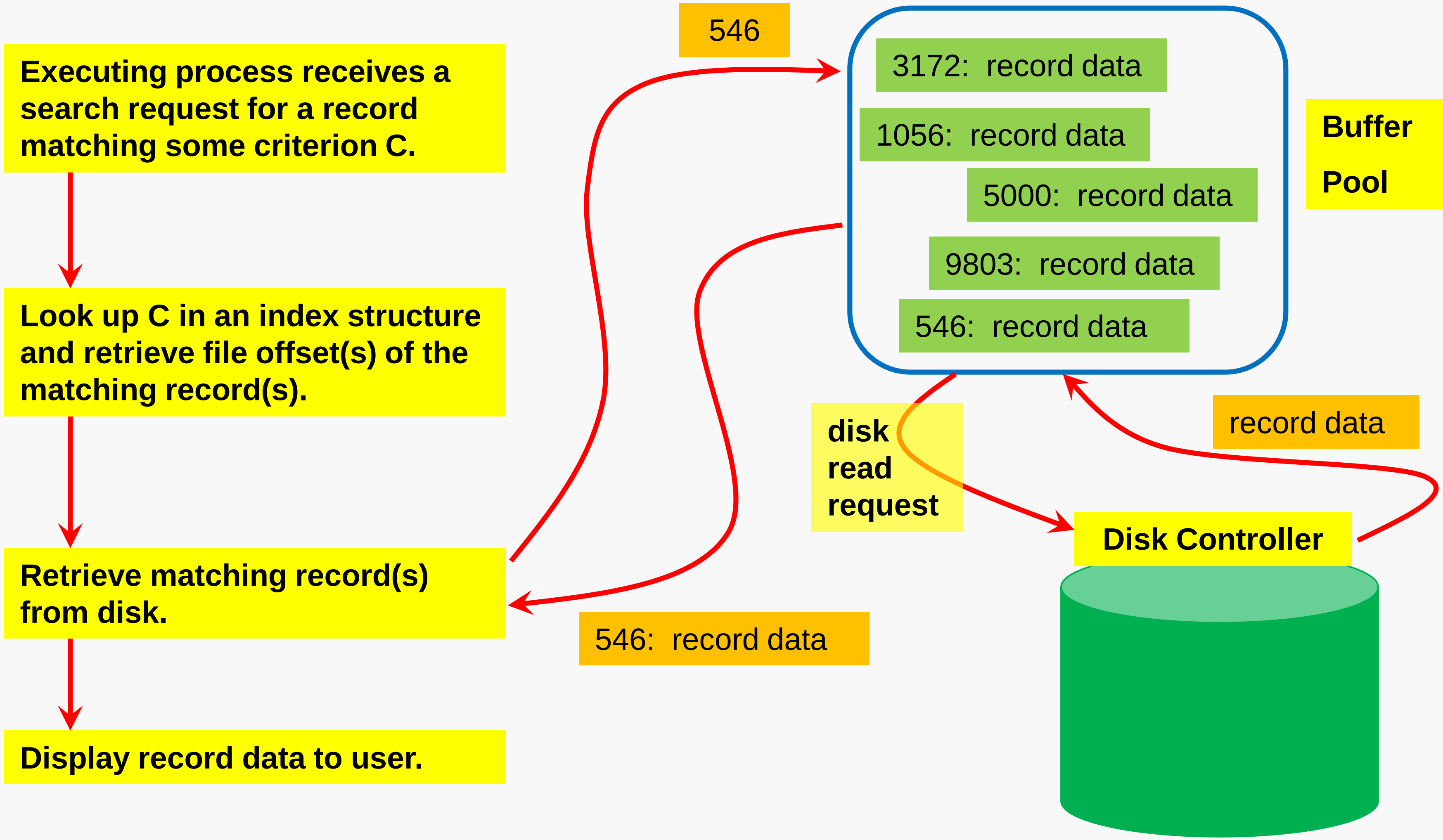
When we get a “hit”, we don’t go to disk:



Retrieving Records using a Buffer Pool

The interaction of the rest of the process with the disk is now mediated by the pool.

When we get a “miss”, the pool goes to disk, updates itself, and serves up the record:



Replacement Strategies

The buffer pool must be organized physically and logically.

The physical organization is generally an ordered list of some sort.

The logical organization depends upon how the buffer pool deals with the issue of replacement — if a new record must be added to the pool and all the buffers are currently full, one of the current records must be replaced.

If the replaced element has been modified, it (usually) must be written back to disk or the changes will be lost. Thus, some replacement strategies may include a consideration of which buffer elements have been modified in choosing one to replace.

Some common buffer replacement strategies:

- FIFO (first-in is first-out) organize buffers as a queue
- LFU (least frequently used) replace the least-accessed buffer
- LRU (least recently used) replace the longest-idle buffer

Example: FIFO Replacement

Logically the buffer pool is treated as a queue:

```
   655:   655   miss
   289:   655   289   miss
   586:   655   289   586   miss
   289:   655   289   586   hit
   694:   655   289   586   694   miss
   586:   655   289   586   694   hit
   655:   655   289   586   694   hit
   138:   655   289   586   694   138   miss
   289:   655   289   586   694   138   hit
   694:   655   289   586   694   138   hit
   289:   655   289   586   694   138   hit
   694:   655   289   586   694   138   hit
   851:   289   586   694   138   851   miss
   586:   289   586   694   138   851   hit
   330:   586   694   138   851   330   miss
   289:   694   138   851   330   289   miss
   694:   694   138   851   330   289   hit
   331:   138   851   330   289   331   miss
   289:   138   851   330   289   331   hit
   694:   851   330   289   331   694   miss
Number of accesses:  20
Number of hits:      10
Number of misses:    10
Hit rate:            50.00
```

Takes no notice of the access pattern exhibited by the program. Consider what would happen with the sequence:

655

289

655

393

655

127

655

781

. . .

Example: LFU Replacement

For LFU we must maintain an access count for each element of the buffer pool. It is also useful to keep the elements sorted by that count.

```
  655:  (655, 1)   miss
  289:  (655, 1)  (289, 1)   miss
  586:  (655, 1)  (289, 1)  (586, 1)   miss
  289:  (289, 2)  (655, 1)  (586, 1)   hit
  694:  (289, 2)  (655, 1)  (586, 1)  (694, 1)   miss
  586:  (289, 2)  (586, 2)  (655, 1)  (694, 1)   hit
  655:  (289, 2)  (586, 2)  (655, 2)  (694, 1)   hit
  138:  (289, 2)  (586, 2)  (655, 2)  (694, 1)  (138, 1
  289:  (289, 3)  (586, 2)  (655, 2)  (694, 1)  (138, 1
  694:  (289, 3)  (586, 2)  (655, 2)  (694, 2)  (138, 1
  289:  (289, 4)  (586, 2)  (655, 2)  (694, 2)  (138, 1
  694:  (289, 4)  (694, 3)  (586, 2)  (655, 2)  (138, 1
  851:  (289, 4)  (694, 3)  (586, 2)  (655, 2)  (851, 1
  586:  (289, 4)  (694, 3)  (586, 3)  (655, 2)  (851, 1
  330:  (289, 4)  (694, 3)  (586, 3)  (655, 2)  (330, 1
  289:  (289, 5)  (694, 3)  (586, 3)  (655, 2)  (330, 1
  694:  (289, 5)  (694, 4)  (586, 3)  (655, 2)  (330, 1
  331:  (289, 5)  (694, 4)  (586, 3)  (655, 2)  (331, 1
  289:  (289, 6)  (694, 4)  (586, 3)  (655, 2)  (331, 1
  694:  (289, 6)  (694, 5)  (586, 3)  (655, 2)  (331, 1
Number of accesses:  20
Number of hits:      12
Number of misses:    8
Hit rate:            60.00
```

Aside from cost of storing and maintaining counter values, and searching for least value, consider the sequence:

655 (500 times)

289 (500 times)

100

101

102

103

. . .

LRU Replacement

With LRU, we may use a simple list structure. On an access, we move the targeted element to the front of the list. That puts the least recently used element at the tail of the list.

```
   655:  655   miss
   289:  289  655   miss
   586:  586  289  655   miss
   289:  289  586  655   hit
   694:  694  289  586  655   miss
   586:  586  694  289  655   hit
   655:  655  586  694  289   hit
   138:  138  655  586  694  289   miss
   289:  289  138  655  586  694   hit
   694:  694  289  138  655  586   hit
   289:  289  694  138  655  586   hit
   694:  694  289  138  655  586   hit
   851:  851  694  289  138  655   miss
   586:  586  851  694  289  138   miss
   330:  330  586  851  694  289   miss
   289:  289  330  586  851  694   hit
   694:  694  289  330  586  851   hit
   331:  331  694  289  330  586   miss
   289:  289  331  694  330  586   hit
   694:  694  289  331  330  586   hit
Number of accesses:  20
Number of hits:      11
Number of misses:    9
Hit rate:            55.00
```

Consider what would happen with the sequence:

655

289

655

301

302

303

304

289

. . .

Aside: Belady's Anomaly

You would (perhaps) expect that if you increased the number of slots in the pool, then for the same sequence of record references you'd get fewer misses (or at least not get more misses).

You may be disappointed, at least if you use FIFO replacement:

```
Record      Pool of size 3
            X  X  X
   1        1  X  X
   2        1  2  X
   3        1  2  3
   4        2  3  4
   1        3  4  1
   2        4  1  2
   5        1  2  5
   1        1  2  5  hit!
   2        1  2  5  hit!
   3        2  5  3
   4        5  3  4
   5        5  3  4  hit!
```

```
Record      Pool of size 4
            X  X  X  X
   1        1  X  X  X
   2        1  2  X  X
   3        1  2  3  X
   4        1  2  3  4
   1        1  2  3  4  hit!
   2        1  2  3  4  hit!
   5        2  3  4  5
   1        3  4  5  1
   2        4  5  1  2
   3        5  1  2  3
   4        1  2  3  4
   5        2  3  4  5
```

L A Belady, R A Nelson, G S Shedler
An anomaly in space-time characteristics of certain programs running in a paging machine
CACM Volume 12, Issue 6, June 1969

Measuring Performance

The performance of a replacement strategy is commonly measured by its *fault rate*, i.e., the percentage of requests that require a new element to be loaded into the pool.

Some observations:

- misses will occur unless the pool contains the entire collection of data objects that are needed (the *working set*)
- which data objects are needed tends to change over time as the program runs, so the working set varies over time
- if the buffer pool is too small, it may be impossible to keep the current working set resident (in the buffer pool)
- if the buffer pool is too large, the program will waste memory

Comparison

None of these replacement strategies, or any other feasible one, is best in all cases.

All are used with some frequency.

Intuitively, LRU and LFU make more sense than FIFO.

The performance you get is determined by the access pattern exhibited by the running program, and that is often impossible to predict.

Belady's optimal replacement strategy:

replace the element whose next access lies furthest in the future

Sometimes stated as "replace the element with the maximal forward distance".

Requires knowing the future, and so is impossible to implement.

Does suggest considering predictive strategies.

Estimating Forward Distance

Ideal replacement strategy:

Replace an element whose forward distance is maximal.

QTPs:

By what logic does FIFO estimate forward distance?

By what logic does LFU estimate forward distance?

By what logic does LRU estimate forward distance?

What about Spatial Locality?

A buffer pool can service temporal locality:

Keep the fetched record around in RAM for awhile…

QTP: how could buffer pool service spatial locality?

Buffer Pool Design

There are some general properties a good buffer pool will have:

- the buffer size and number of buffers should be client-configurable
- the buffer pool may deal only in "raw bytes"; i.e., not know anything at all about the internals of the data record format used by the client code

  OR

  the buffer pool may deal in interpreted data records, parsed from the file and transformed into an object
- if records are fixed-length then each buffer should hold an integer number of records; for variable-length records, things are more complex and it is often necessary for buffers to allow some internal fragmentation
- empirically, a program using a buffer pool is considered to be achieving good performance if less than 10% of the record references require loading a new record into the buffer pool