Locality-aware Buffer Management to Speedup Disk Accesses

(Progress Report)

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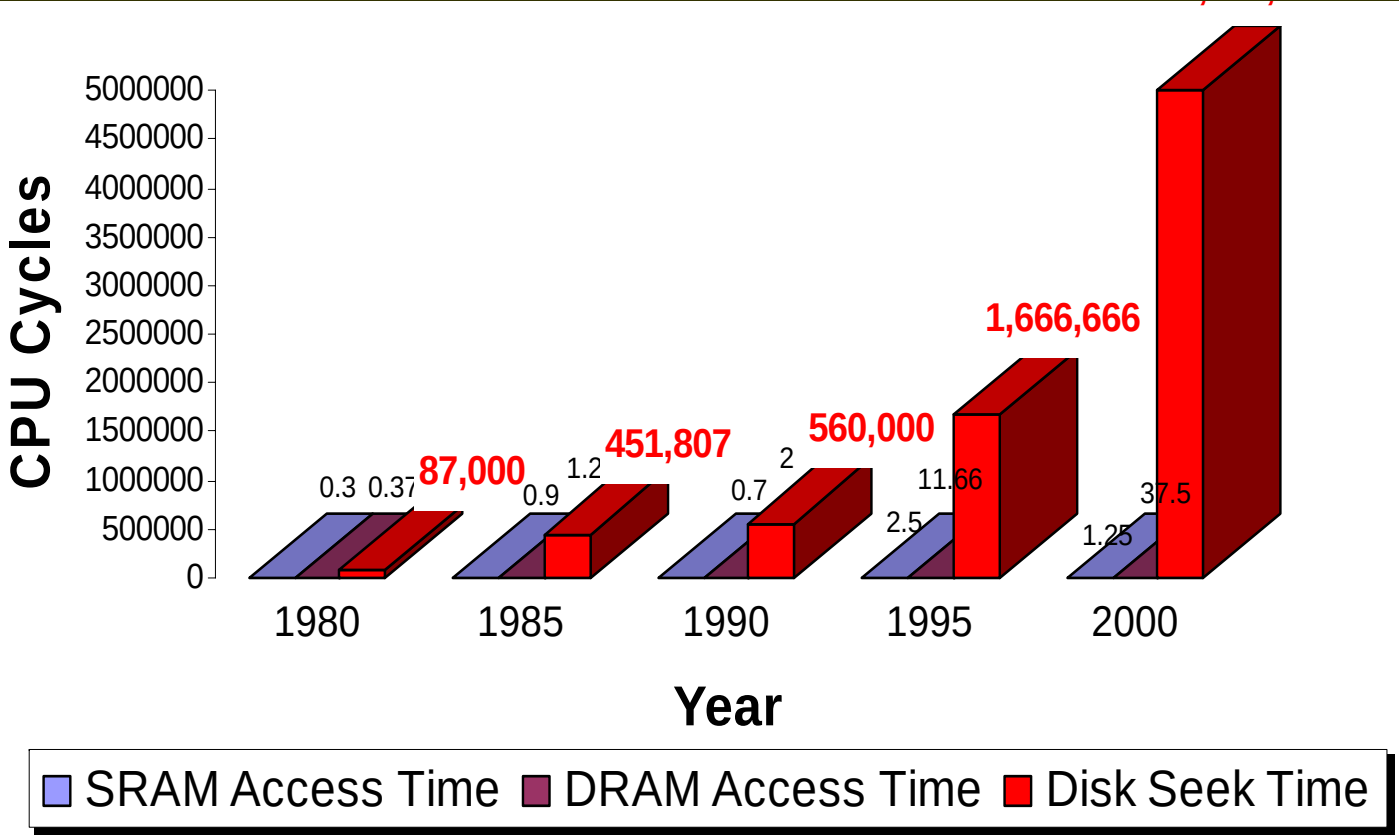
"Disk Wall" is an Critical Issue

- Many data-intensive applications generate huge data sets in disks world wide in very fast speed.
  - Stanford Linear Accelerator's BaBar detector generates 1 TB/day in PEP-II Storage Ring.
  - LANL Turbulence Simulation: processing 100+ TB.
  - Google searches and accesses over 10 billion web pages and tens of TB data in Internet.
  - Internet traffic is expected to increase from 1 to 16 million TB/month due to multimedia data.
  - We carry very large digital data, films, photos, …
- Data home is the cost-effective & reliable Disks
  - Slow disk data access is the major bottleneck

The disks in 2000 are 57 times "SLOWER" than their ancestors in 1980 --- increasingly widen the Speed Gap between Peta-Scale computing and Peta-Byte acesses.



Bryant and O'Hallaron, "Computer Systems: A Programmer's Perspective", Prentice Hall, 2003

Two Major Factors Limiting Disk Performance

- Disk speed is limited by mechanical constraints.
  - seek/rotation (random access is slow/high power)
- Access of sequential blocks is fastest.
- OS is not disk-layout aware
  - Limited info for I/O data caching and prefetching

Randomly Scattered Disk Accesses

- Scientific computing
  - Scalable IO (SIO) Report: “in many applications majority of the requests are for small amount of data (less than a few Kbytes)” [Reed 1997]
  - CHARISMA Report: “large, regular data structures are distributed among processes with interleaved accesses of shared files” [Kotz 1996]
- Workloads on popular operating systems
  - UNIX: most accessed files are short in length (80% are smaller than 26 Kbytes) [Ousterhout,1991]
  - Windows NT: 40% I/O operations are to files shorter than 2KBytes [Vogels, 1999]

Random and Scattered Disk Accesses Caused by Multiple Sequential Objects

- Modern disk arrays:
  - HP FC-60 disk arrays: “Most workloads have a range of small and large jumps in sequential accesses and interferences between concurrent access streams”. [Keeton 2001]
  - Detecting sources of irregular disk access patterns: “Although sequential full-file access is relatively common, most data objects are much smaller than the disk request sizes needed to achieve good efficiency.” [Shindler 2002]
- Peta-Byte data analysis is very slow:
  - Many Peta-Bytes of active data for BaBar expperiments
  - Data analysis: random analysis of small blocks.
  - A researcher has several hundred data streams in batch mode
  - Several hundred concurrent researchers are active.

Existing Approaches and Limits

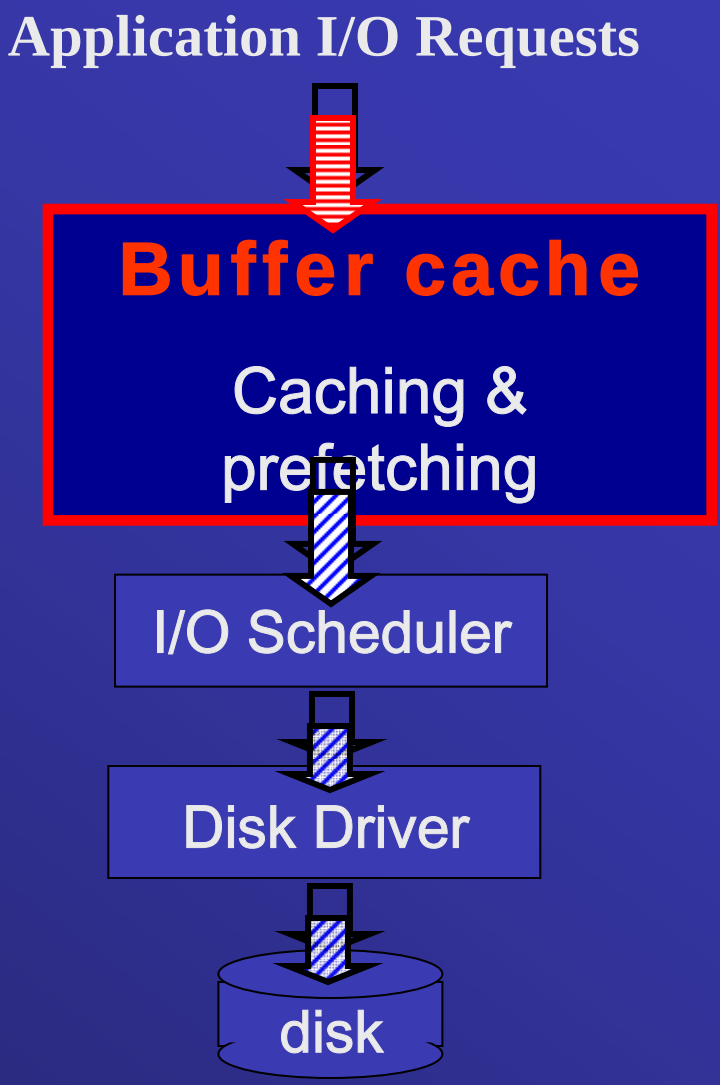
- Programming for Disk Performance
  - Hiding disk latency by overlapping computing
  - Sorting large data sets (SIGMOD'97)
  - Application dependent and programming burden
- Transparent and Informed Prefetching (TIP)
  - Applications issue hints on their future I/O patterns to guide prefetching/caching (SOSP'99)
  - Not a general enough to cover all applications
- Collective I/O: gather multiple I/O requests
  - make contiguous disk accesses for parallel programs

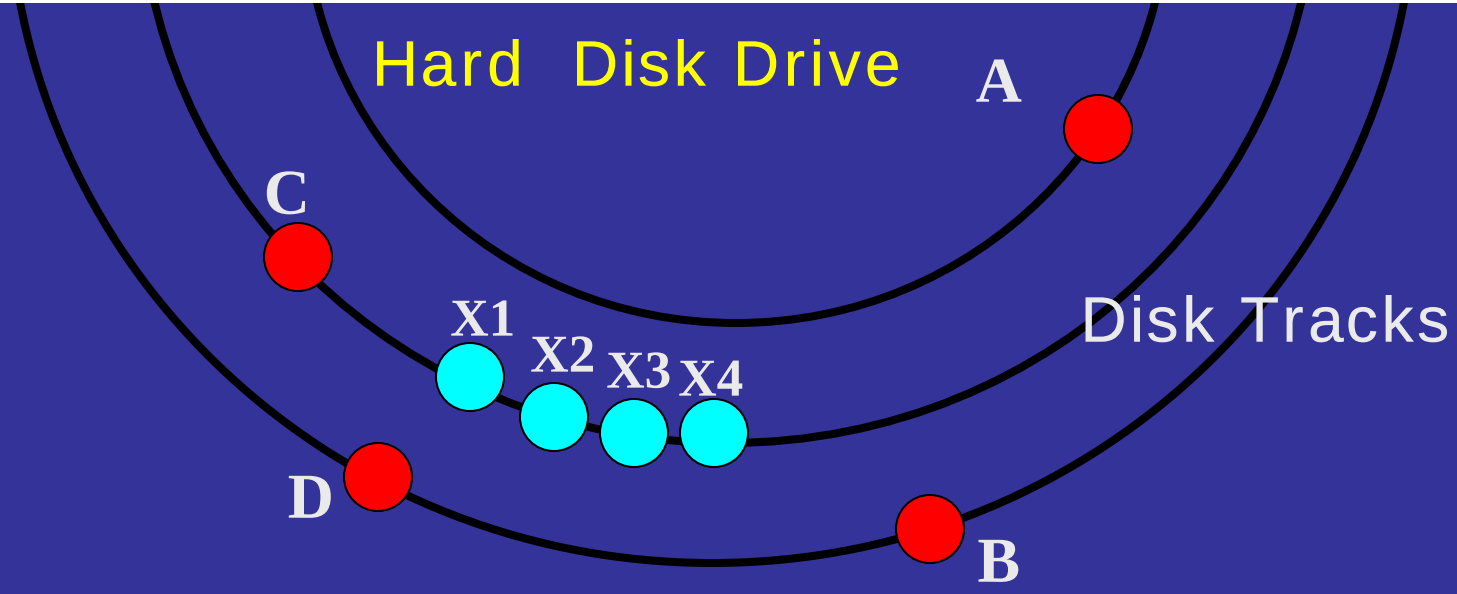
Our Objectives

- Reducing buffer cache miss penalty
  - by minimizing random disk accesses
  - making disk-aware caching and prefetching
- Application independent approach
  - putting disk access information on OS map
  - Exploiting DUal LOcalities (DULO):
    - temporal locality of program execution
    - spatial locality of disk accesses

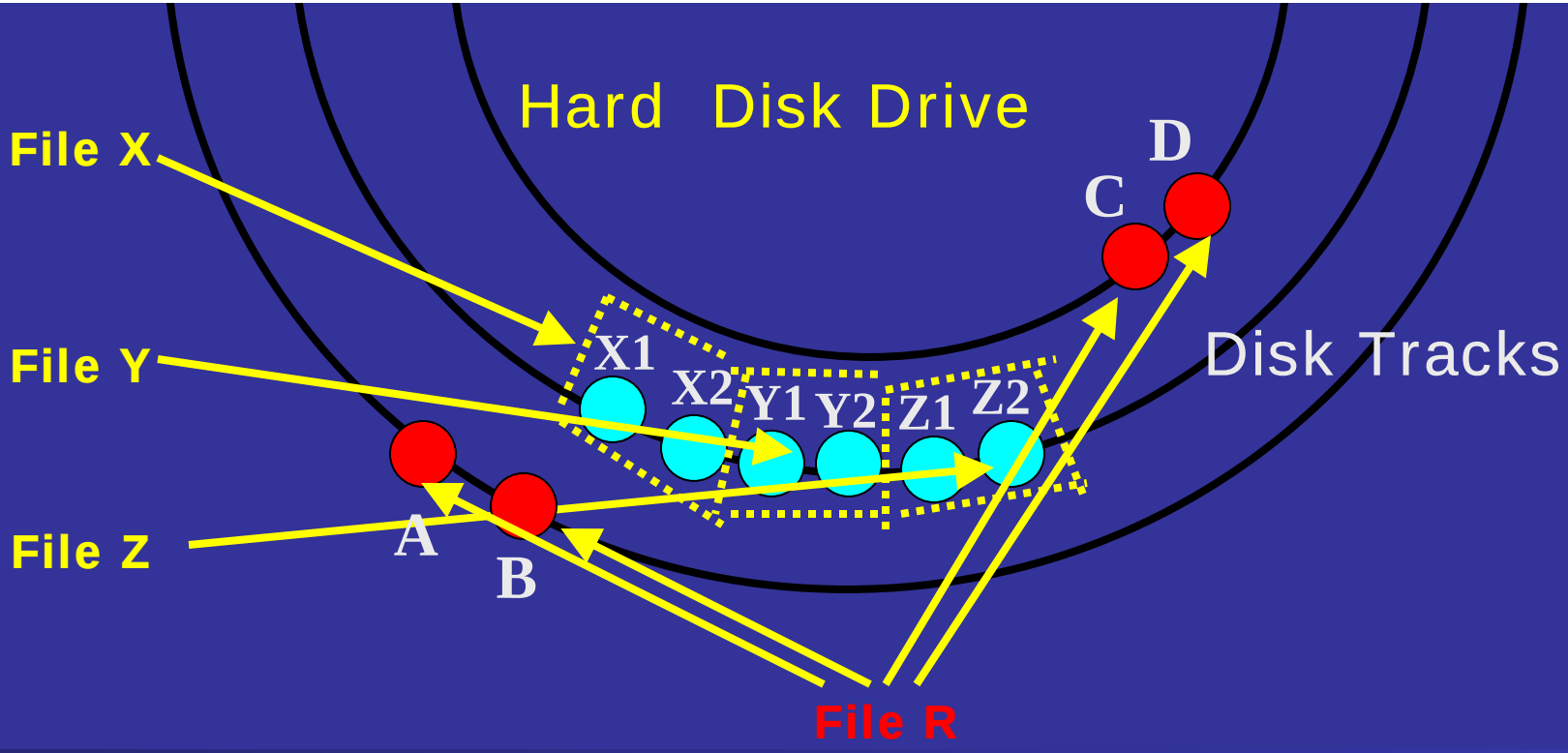
What is Buffer Cache Aware and Unaware?

- Buffer is an agent between I/O requests and disks.
  - aware access patterns in time sequence (in a good position to exploit temporal locality)
  - unaware physical layout (no effort to exploit spatial locality in disks)
- Existing functions
  - send unsatisfied requests to disks
  - **LRU replacement by temporal locality**
  - generate prefetching requests to disks.
- I/O scheduler is not effective: spatial locality is not aware in buffer cache.





- Unique and critical roles of buffer cache
- Buffer cache can influence request stream patterns in disks
- If buffer cache is disk-layout-aware, OS is able to
  - Distinguish sequentially and randomly accessed blocks
  - Give “expensive” random blocks a high caching priority
  - replace long sequential data blocks timely to disks
  - Disk accesses become more sequential.



- Performance is low by logic file abstraction based prefetch.
  - Sequential accesses spanning multiple small files cannot be detected.
  - Sequential layout in logic abstraction may not be sequential layout on physical disk.
  - Detected sequences of blocks are not remembered.

Opportunities and Challenges

- With Disk Spatial Locality (Disk-Seen)
  - Buffer cache exploits Dual Localities (DULO)
  - Address the limits of both caching and prefetching
- A Disk-Seen System Infrastructure
  - analyze and utilize disk-layout Information
  - accurately and timely identify long disk sequences
  - consider trade-offs of temporal and spatial locality (buffer cache hit ratio vs miss penalty)
  - manage its data structures with low overhead
  - Implement it in OS kernel for practical usage

Disk-Seen Task 1: Make Disk Layout Info. Available

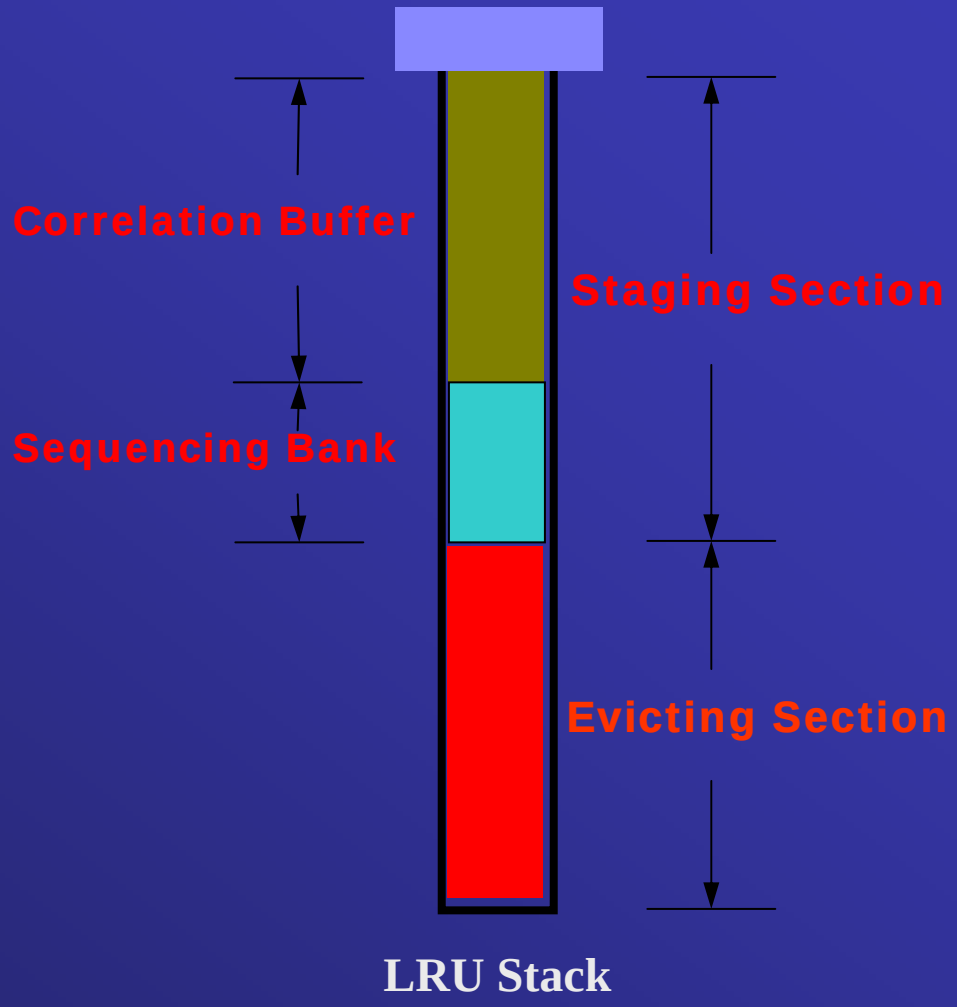
- Which disk layout information to use?
  - Logical block number (LBN): location mapping provided by firmware. (each block is given a sequence number)
  - Accesses of contiguous LBNs have a performance close to accesses of contiguous blocks on disk. (except bad blocks occur)
  - The LBN interface is highly portable across platforms.
- How to efficiently manage the disk layout information?
  - LBN is only used to identify disk locations for read/write;
  - We want to track access times of disk blocks and search for access sequences via LBNs;
  - Disk block table: a data structure for efficient disk blocks tracking.

Disk-Seen TASK 2: Exploiting Dual Localities (DULO)

- **Sequence Forming**

  Sequence ---- a number of blocks whose disk locations are adjacent and have been accessed during a limited time period.

- **Sequence Sorting** based on its recency (temporal locality) and size (spatial locality)



Disk-Seen TASK 3: DULO-Caching

Adapted GreedyDual Algorithm

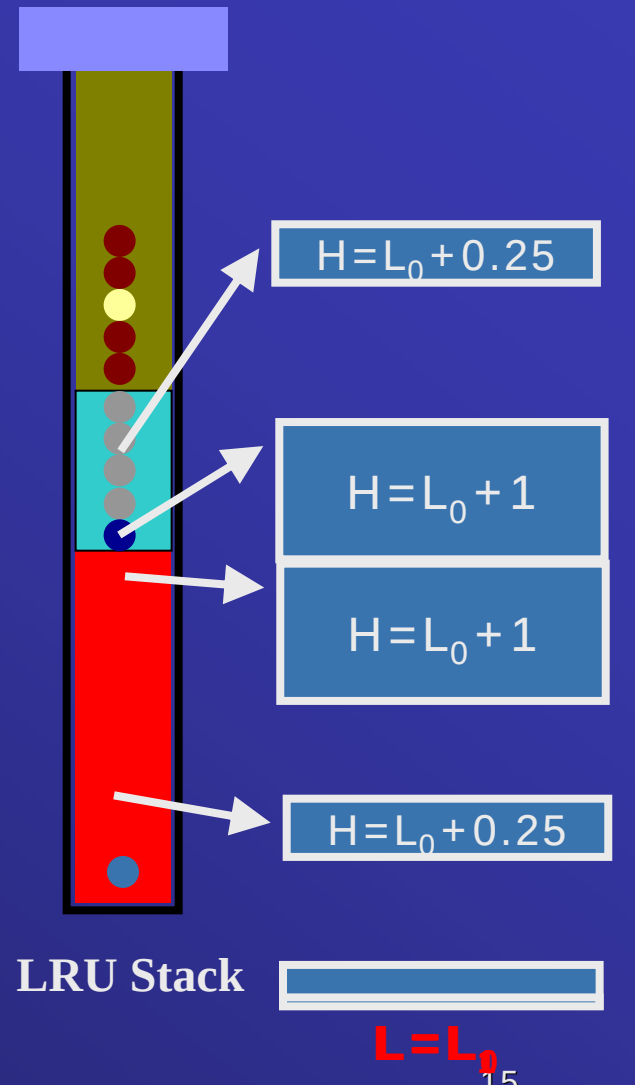
- a global inflation value L , and a value H for each sequence
- Calculate H values for sequences in sequencing bank:

  H = L + 1 / Length(sequence)

  Random blocks have larger H values
- When a sequence (s) is replaced,

  L = H value of s .

  L increases monotonically and make future sequences have larger H values
- Sequences with smaller H values are placed closer to the bottom of LRU stack

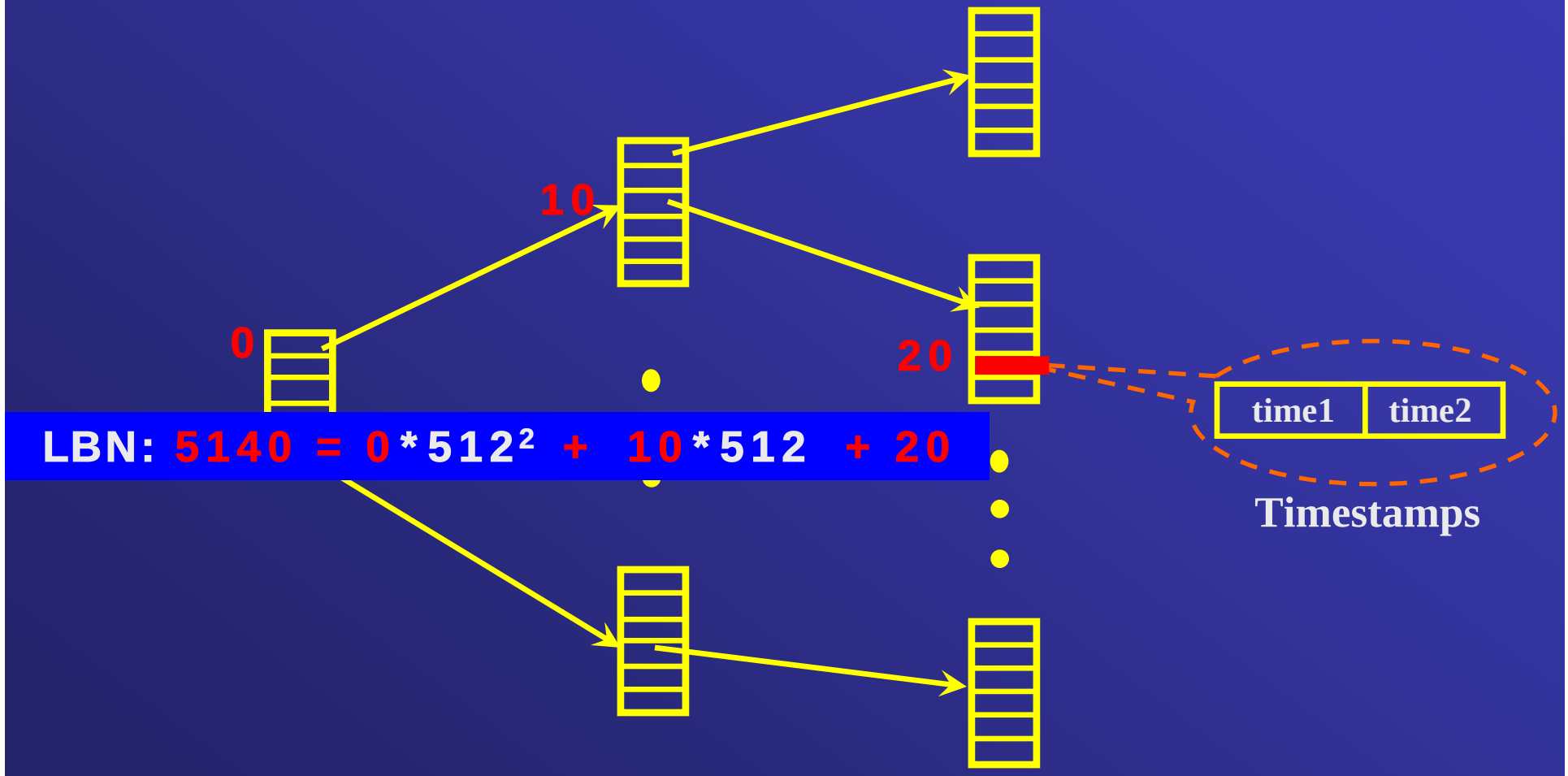


DULO-Caching Principles

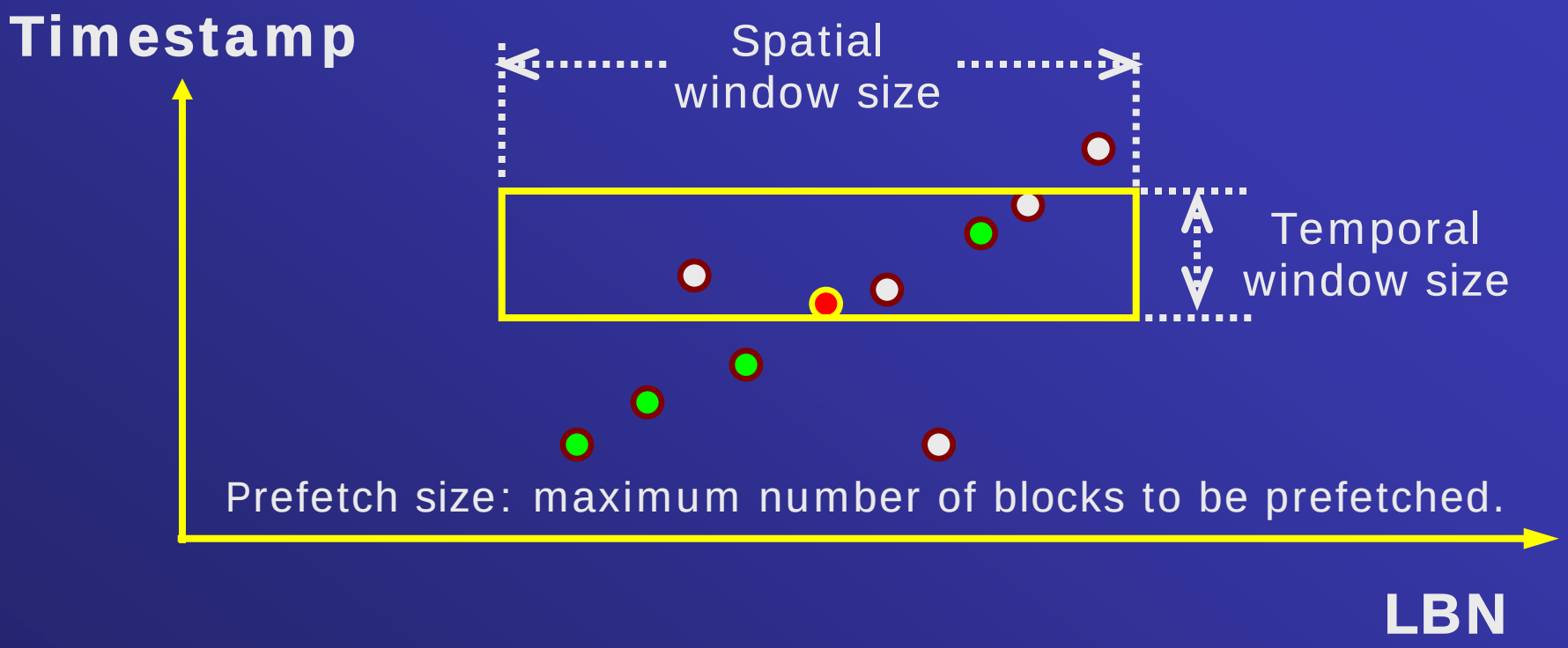
- Moving long sequences to the bottom of stack
  - replace them early, get them back fast from disks
- Replacement priority is set by sequence length.
- Moving LRU sequences to the bottom of stack
  - exploiting temporal locality of data accesses
- Keeping random blocks in upper level stack
  - hold them: expensive to get back from disks.

Disk-Seen Task 4: Identifying Long Disk Sequence

a data structure for tracking disk blocks

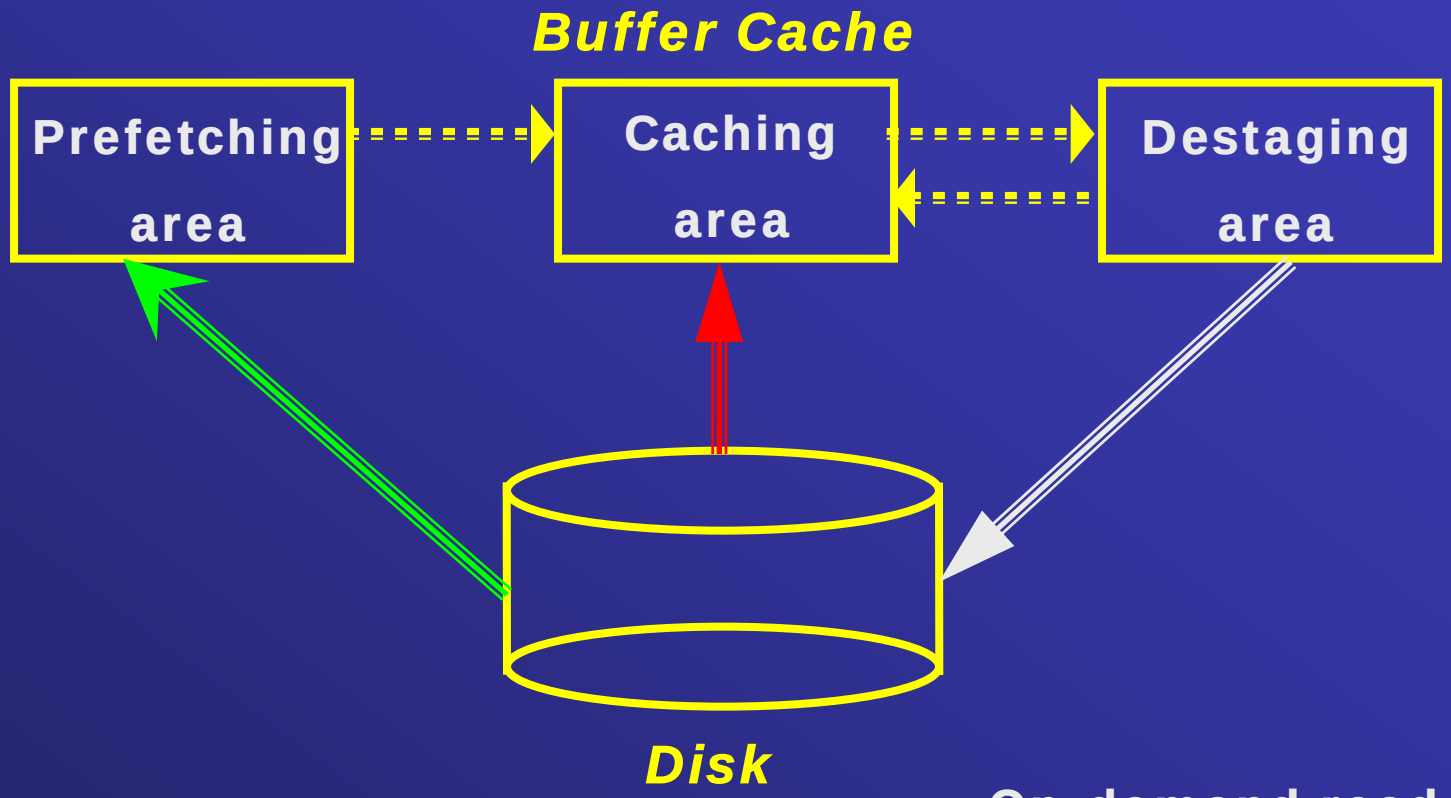


Disk-Seen Task 5: DULO-Prefetching



- Block initiating prefetching
- Resident block
- Non-resident block

DiskSeen: a System Infrastructure to Support DULO-Caching and DULO-Prefetching



Block transfers between areas

On-demand read: place in stack top

DULO-Prefetching: adj. window / stream

DULO-Caching: LRU blks and Long seqs.

Conclusions

- Disk performance is limited by
  - Non-uniform accesses: fast sequential, slow random
  - OS buffer management is Disk-layout unaware.
- The buffer cache is a critical component for I/O.
  - temporal locality of program execution is used only.
- Building a Disk-Seen system infrastructure for
  - DULO-Caching
  - DULO-Prefetching
- The size of the block table is 0.1% (4 K block) of disk capacity. Its working set can be in buffer cache.

References

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- ULC: multi-level storage caching, ICDCS'04.
- Clock-Pro: Linux VM page replacement, USENIX'05.
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- SmartSaver: Saving disk energy by Flash M, ISLPED'06
- Measurements of BitTorrent, SIGCOMM IMC'05.
- Measurements of streaming quality, SIGCOMM IMC'06.
- DULO-prefetching: OS kernel enhancement, USENIX'07.