Relational Database System Implementation

CS122 – Lecture 2

Winter Term, 2018-2019

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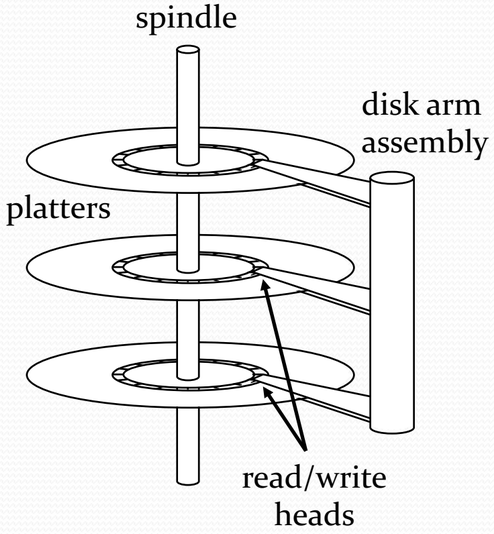
2018–2019冬季学期

Magnetic Disks

- Magnetic disks are most widely used online storage medium in computers
  - Hard disk drives (HDD)
- Drive contains some number of *platters* mounted on a *spindle*
  - Platters spin at a constant rate of speed
  - 5400 RPM, up to 15000 RPM
- Read/write heads are suspended above platters on a *disk arm*
  - All heads move together as a unit



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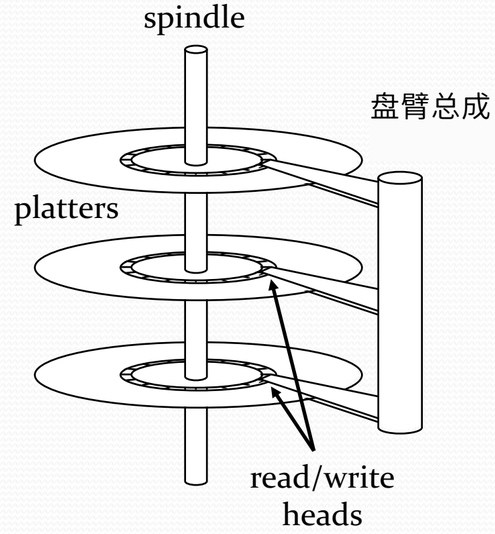
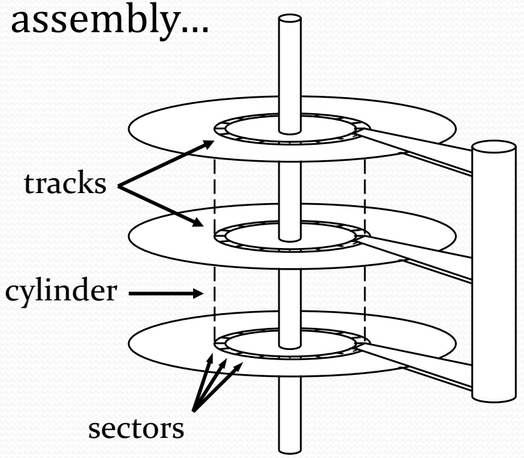
磁盘

磁盘是使用最广泛的在线存储
  计算机中的介质
    硬盘驱动器(HDD)
驱动器包含一些
  安装在主轴上的盘片
    盘片以恒定的速度旋转
      速度率
    5400RPM，最高15000RPM
读写头暂停
  磁盘臂上的盘片上方
    所有头部作为一个整体一起移动



Magnetic Disks (2)

- Platters are divided into *tracks*
- Tracks are divided into *sectors*
  - Modern drives have more sectors towards edge of disk
- All heads are positioned by one assembly...
  - A *cylinder* is made up of the tracks on all platters at the same position
- To read a sector from disk:
  - Assembly *seeks* to the appropriate cylinder
  - Sector is read when it rotates under the disk head



磁盘(2)

盘片被划分为磁道磁道被划分为扇区

现代驱动器在磁盘边缘有更多扇区

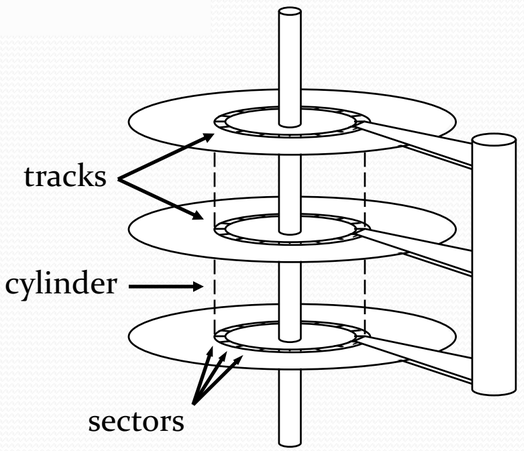
所有头都由一个组件定位……

气缸由
同一位置的所有盘片上的轨道

从磁盘读取扇区：

大会寻求
合适的气缸

扇区在旋转时被读取
磁头下



Disk Performance Measures

- *Access time* is the time between a read/write request being issued, and the data being returned
  - Read/write heads must be moved to appropriate track
  - Sectors must rotate past the read/write heads
- First operation is called a *seek*
  - Average seek time of a disk is measured from a series of random seeks (uniform distribution)
  - Generally ranges from 3-15ms
  - Typical consumer drives are in the range of 9-12ms
- Seeking nearby tracks will obviously be faster
  - Track-to-track seek times in range of 0.2-0.8ms
- (SSDs have “seek times” in the 0.08-0.16ms range)

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磁盘性能测量

访问时间是读写请求之间的时间
发出，并返回数据

读写头必须移动到适当的轨道扇区必须旋转经过读写头

第一个操作称为查找

磁盘的平均寻道时间是从一系列
随机搜索（均匀分布）

一般范围为3–15ms典型的消费类驱动器在9–12ms
范围内

寻找附近的曲目显然会更快

磁道到磁道寻道时间在0.2–0.8ms范围内

（SSD的“寻道时间”在0.08–0.16ms范围内）

Disk Performance Measures (2)

- *Rotational latency time* is amount of time for sector to pass under read/write heads
  - Average rotational latency is ½ the time for a full rotation
  - 5,400 RPM: 5.6ms
  - 7,200 RPM: 4.2ms
  - 15,000 RPM: 2ms
- Disks can only read/write information so quickly
  - *Data transfer rate* specifies how fast data is read from/written to the disk
  - Current interfaces can support up to 600+ MB/sec
  - Actual transfer rate depends on several things:
    - The disk and its controller, motherboard chipset, etc.
    - The section of the disk being accessed

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磁盘性能测量(2)

旋转延迟时间是扇区从
通过读写头

平均旋转延迟是完整旋转时间的 5 400RPM：5.6ms7 20
0RPM：4.2ms15 000RPM：2ms

磁盘只能如此快速地读取写入信息

数据传输率指定从写入到读取数据的速度
到磁盘

当前接口可以支持高达600+MB秒实际传输速率取
决于几个因素：

磁盘及其控制器、主板芯片组等。
正在访问的磁盘部分

Disk-Access Optimizations

- Wide range of techniques used to improve hard disk performance
  - Implemented in the HDD itself, and/or in operating system
- Buffering
  - When data is read, store it in a memory buffer
  - If same data is requested again, provide it from the buffer
- Read-ahead
  - When a sector is read, read other sectors in the same track
  - If a program is scanning through a file, subsequent accesses can be satisfied immediately from cache

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Disk-Access Optimizations

用于改进硬盘的各种技术

performance

在HDD本身和/或操作系统中实现

- Buffering

读取数据时，将其存储在内存缓冲区中

如果再次请求相同的数据，则从缓冲区提供

- Read-ahead

读取一个扇区时，读取同一磁道中的其他扇区

如果程序正在扫描文件，后续访问

可以立即从缓存中满足

Disk-Access Optimizations (2)

- I/O Scheduling
  - The hard disk can queue up batches of read and write requests, then schedule them in a reasonable way
  - Goal: reduce the average seek time of accesses
  - Writes can be buffered in volatile memory to facilitate this (can cause problems if power fails before write is performed)
- Nonvolatile write buffers
  - Disk provides NV-RAM to cache disk writes
  - Data is saved in NV-RAM before being saved to disk
  - Data isn't written to disk until the disk is idle, or the NV-RAM buffer is full
  - If power fails, contents of NV-RAM are still intact!

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Disk-Access Optimizations (2)

- I/O Scheduling

硬盘可以排队批量读写
请求，然后以合理的方式安排它们

目标：减少访问的平均寻道时间

写操作可以缓冲在易失性存储器中，以促进这一点
（如果在执行写入之前断电可能会导致问题）

非易失性写缓冲器

磁盘提供NV-RAM来缓存磁盘写入

数据在保存到磁盘之前先保存在NV-RAM中

在磁盘空闲或NV-RAM之前，数据不会写入磁盘
缓冲区已满

如果断电，NV-RAM的内容仍然完好无损！

Disk-Access Optimizations (3)

- RAID (Redundant Array of Independent Disks)
  - Employed for both performance and reliability reasons
  - One storage device can transfer up to 600MB/s
  - Processor memory bus can transfer GB/s
  - Idea: Access multiple storage devices in parallel
    - Data is either duplicated on multiple devices, or it is striped across multiple devices
    - A RAID controller translates logical accesses into corresponding accesses on the appropriate device(s)

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Disk-Access Optimizations (3)

RAID（独立磁盘冗余阵列）

出于性能和可靠性的考虑而受聘

一个存储设备最多可传输600MBs

处理器内存总线可以传输GBs

理念：并行访问多个存储设备

数据在多个设备上重复，
或者跨多个设备条带化

RAID控制器将逻辑访问转换为
相应设备上的相应访问

Solid State Drives

- Solid State Drives are becoming increasingly common
  - Still more expensive and smaller than HDDs
  - (This trend will likely continue for a number of years)
- Use flash memory chips to provide persistent storage
  - Most common is NAND flash memory, which is read/written in 512B-4KB pages (similar to HDDs)
- Reads are very fast: on the order of a few µs
  - No seek time or rotational latency whatsoever!
  - (Still slower than main memory, of course)
- Write performance can be much more varied…

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固态硬盘

固态硬盘正变得越来越普遍

仍然比HDD更昂贵且体积更小

（这种趋势可能会持续数年）

使用闪存芯片提供持久存储

最常见的是NAND闪存，即

读取写入512B–4KB页（类似于HDD）

读取速度非常快：大约几微秒

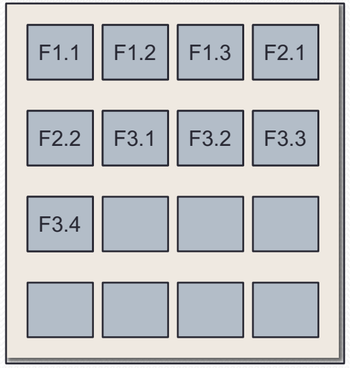
没有任何寻道时间或旋转延迟！

（当然还是比主存慢）

写入性能可以更加多样化……

Solid State Drives (2)

- SSDs are comprised of flash memory blocks
  - Each block can hold e.g. 4KB of data
  - As usual, break data files into blocks
- Example: three files on our SSD: F1, F2 and F3
- SSDs must follow specific rules when writing to blocks:
  - SSDs can only write data to blocks that are currently empty
  - Cannot modify a block that already contains data



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固态硬盘(2)

SSD由闪存块组成

每个块可以容纳例如4KB数据

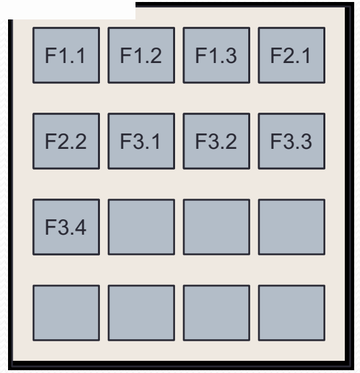
像往常一样，将数据文件分成块

示例：我们SSD上的三个文件：F1、F2和F3SSD必须遵循特定规则

写入块：

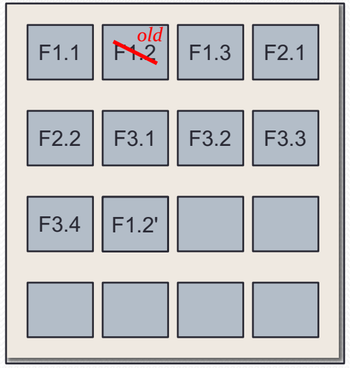
SSD只能将数据写入
目前为空

不能修改已经存在的块
包含数据



Solid State Drives (3)

- SSDs can only write to blocks that are currently empty
- Example: we want to modify the data in block 2 of F1
  - Can't just change the data in-place!
- Instead, must write a new version of F1.2
  - SSD marks old version of F1.2 as not in use, and stores a new version F1.2'



- **SSD Issue 1:**
  - SSDs aren't good at disk structures that require frequent in-place modifications

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固态硬盘(3)

SSD只能写入当前为空的块示例：我们要修改F1的第2块中的数据

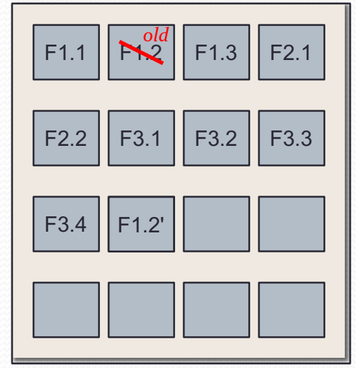
不能就地更改数据!

相反，必须写一个新版本的F1.2

SSD将旧版本的F1.2标记为非正在使用中，并存储新版本F1.2'

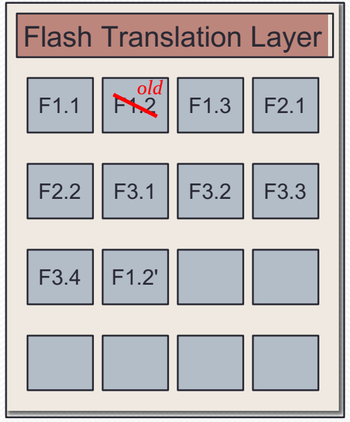
- **SSD Issue 1:**

SSD不擅长以下磁盘结构：需要频繁的就地修改



Solid State Drives (4)

- Don't want applications to have to keep track of the actual blocks that comprise their files…
  - Every time part of an existing file is written to the SSD, a new block must be used
- Solid State Drives also include a Flash Translation Layer that maps logical block addresses to physical blocks
  - This mapping is updated every time a write is performed



固态硬盘(4)

不希望应用程序必须跟踪
组成文件的实际块……

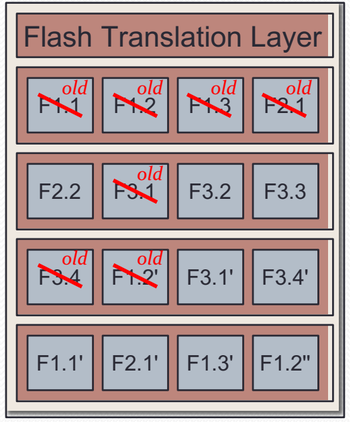
每次将现有文件的一部分写入SSD，
必须使用新块

固态驱动器还包括闪存
将逻辑块地址映射到物理块的转换层

此映射每次更新一次
执行写入

SSDs: Erase Blocks

- Over time, SSD ends up with few or no available cells
  - e.g. a series of writes to our SSD that results in all cells being used, or marked old
- Problem: SSDs can only erase cells in groups
  - Groups are called *erase blocks*
  - A read/write block might be 4-8KiB…
  - Erase blocks are often 128 or 256 of these blocks (e.g. 2MiB)!
- SSDs must periodically clear one or more erase-blocks to free up space
  - Erasing a block takes 1-2 ms to perform



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SSD：擦除块

随着时间的推移，SSD最终会出现很少或没有可用单元

例如对我们的SSD进行一系列写入，导致所有单元正在使用或标记为旧的

问题：SSD只能分组擦除单元格

组被称为擦除块

一个读写块可能是4-8KiB…

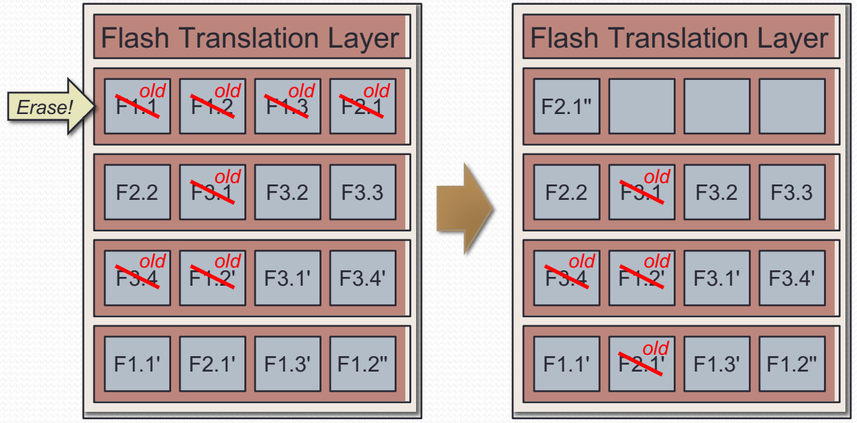
擦除块通常是128或256这些块（例如2MiB）！

SSD必须定期清除一个或更多擦除块以释放空间

擦除一个块需要1-2毫秒来执行

SSDs: Erase Blocks (2)

- Best case is when a whole erase block can be reclaimed
- Example: want to write to F2.1'
  - SSD can clear an entire erase-block and then write the new block



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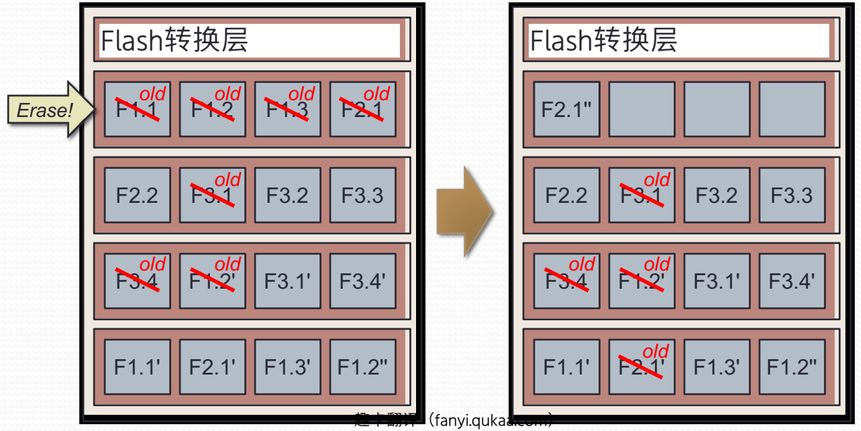
SSD：擦除块(2)

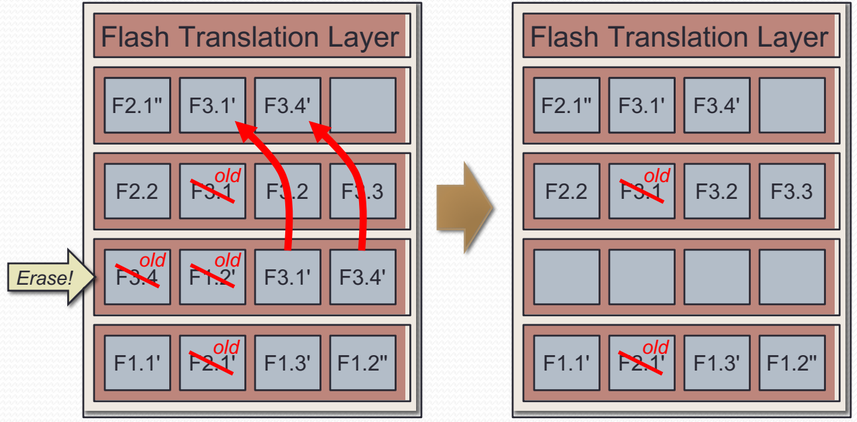
最好的情况是可以回收整个擦除块示例：想要写入F2.1'

SSD可以清除整个擦除块，然后写入新区块



SSDs: Erase Blocks (3)

- More complicated when an erase block still holds data
  - e.g. SSD decides it must reclaim the third erase-block
- SSD must relocate the current contents before erasing
- Example: SSD wants to clear third erase-block



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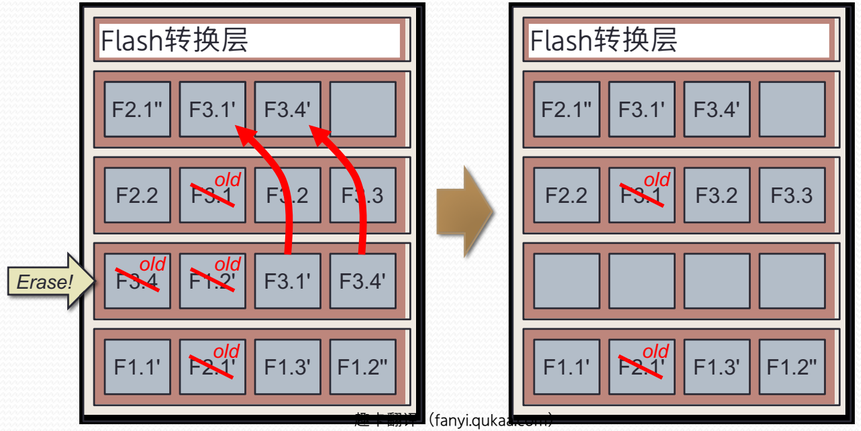
SSD：擦除块(3)

当擦除块仍然保存数据时更复杂

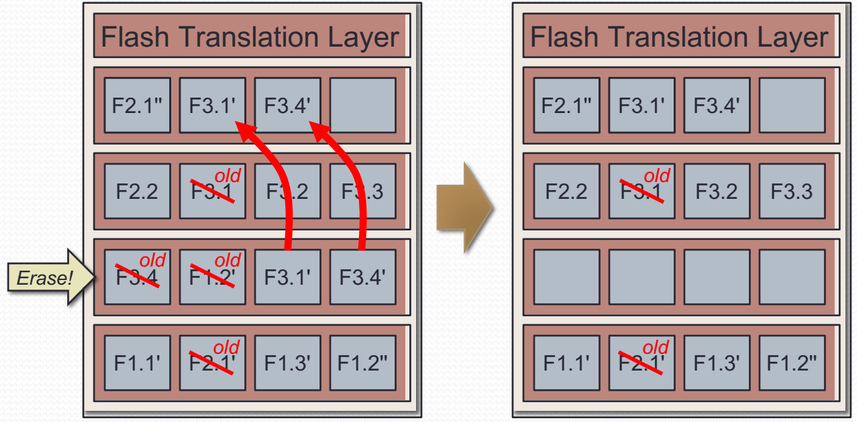
例如SSD决定它必须回收第三个擦除块

SSD必须在擦除之前重新定位当前内容示例：SSD想要清除第三个擦除块



SSDs: Erase Blocks (4)

- **SSD Issue 2**:
  - Sometimes a write *to* the SSD incurs additional writes *within* the SSD
  - Phenomenon is called *write amplification*



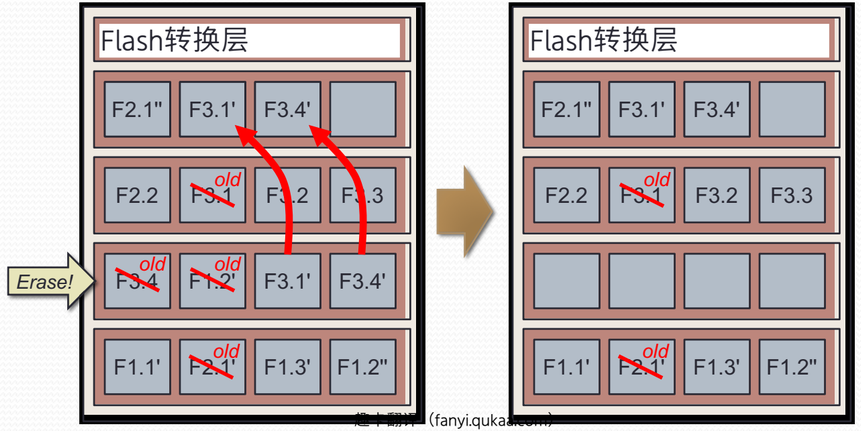
SSD：擦除块(4)

- **SSD Issue 2**:

有时对SSD的写入会导致额外的写入

SSD内

现象称为写放大



SSDs: Erasure and Wear

- A block can only be erased a fixed number of times…
- SSDs ensure that different blocks wear evenly
  - Called *wear leveling*
  - Data that hasn't changed much (*cold data*) is moved into blocks with higher erase-counts
  - Data that has changed often (*hot data*) is moved into blocks with lower erase-counts
- Theoretically, SSDs should last longer than hard disks

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SSD：擦除和磨损

一个块只能被擦除固定的次数……

SSD确保不同块均匀磨损

称为磨损均衡

变化不大的数据（冷数据）被移入
具有较高擦除计数的块

经常变化的数据（热点数据）被移入
具有较低擦除计数的块

从理论上讲，SSD的使用寿命应该比硬盘长

SSDs and HDDs: Failure Modes

- SSDs fail in different ways than hard disks generally do
- Hard disks tend to degrade more slowly over time
  - Sensitive to mechanical shock and vibration
  - Surface defects can slowly become apparent over time
  - Result: usually, data is slowly lost over time (although disk controllers can also burn out, etc.)
- Solid state drives are far less sensitive to mechanical shock and other environmental factors
  - But, SSD controller electronics can fail, particularly due to power surges / outages
  - Result: all the data disappears at once, without warning

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SSD和HDD：故障模式

SSD的故障方式与一般硬盘不同随着时间的推移，硬盘的降级趋于缓慢

- 对机械冲击和振动敏感
- 随着时间的推移，表面缺陷会慢慢变得明显
- 结果：通常，数据会随着时间慢慢丢失（尽管磁盘控制器也可能烧坏等）

固态硬盘对机械设备的敏感性要低得多冲击和其他环境因素

- 但是，SSD控制器电子设备可能会出现故障，尤其是由于电涌停电
- 结果：所有数据立即消失，没有警告

Database External Storage

- Virtually all of our discussion going forward will assume spinning magnetic disks, not solid state drives
  - Data volumes continue to grow, and HDDs are both larger and cheaper than SSDs
  - HDDs will continue to be relevant for the time being
- Observation 1: Solid-state drives obviate some of the issues we will take into account!
  - e.g. designing algorithms and file-storage formats to minimize disk seek overhead
  - There is no seek overhead with SSDs

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数据库外部存储

我们接下来的几乎所有讨论都将
假设旋转磁盘，而不是固态驱动器

数据量持续增长，HDD
比SSD更大更便宜

硬盘驱动器暂时将继续具有相关性

观察1：固态驱动器消除了一些
我们会考虑的问题！

例如设计算法和文件存储格式
最小化磁盘寻道开销

SSD没有寻道开销

Database External Storage (2)

- Most of our discussions assume that there is no overhead for in-place modification of data
- Observation 2: Solid-state drives really aren't capable of modifying data in-place
  - They can present the abstraction, but under the hood, the SSD is doing something completely different
  - SSDs are more efficient with file formats that minimize in-place modification of data
- This is an active area of research

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数据库外部存储(2)

我们的大多数讨论都假设没有
就地修改数据的开销

观察2：固态硬盘真的不行
就地修改数据

他们可以呈现抽象，但在幕后，
SSD正在做一些完全不同的事情

SSD的效率更高，文件格式最小化
就地修改数据

这是一个活跃的研究领域

Database Files

- Databases normally store data in files…
  - The filesystem is provided by the operating system
- Operating system provides several essential facilities:
  - Open a file at a particular filesystem path
  - Seek to a particular location in a file
  - Read/write a block of data in a file
  - (other facilities as well, e.g. memory-mapping a file into a process' address-space)

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数据库文件

数据库通常将数据存储在文件中……

文件系统由操作系统提供

操作系统提供了几个重要的功能：

在特定文件系统路径打开文件

查找文件中的特定位置

读写文件中的数据块

（还有其他功能，例如将文件内存映射到process' address-space)

Database Files (2)

- Operating systems also provide the ability to *synchronize* a file to disk
  - Ensures that all modified data caches are flushed to disk
  - Includes flushing of OS buffers, hard-disk cache, etc.
  - Expectation is that if the operation completes, the data is now persistent (e.g. on the disk platter, or in NV-RAM)
- If the system crashes before a modified file is sync'd to disk, data will very likely be corrupted and/or lost
- Once the file is sync'd, the OS effectively guarantees that the disk state reflects the latest version of the file

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数据库文件(2)

操作系统还提供了以下能力：
- 将文件同步到磁盘
  - 确保所有修改的数据缓存都刷新到磁盘
  - 包括刷新操作系统缓冲区、硬盘缓存等。
  - 期望是如果操作完成，数据是现在持久化（例如在磁盘盘片或NV-RAM中）

如果在修改文件同步到之前系统崩溃
- 磁盘，数据很可能会损坏或丢失

文件同步后，操作系统有效保证
- 磁盘状态反映文件的最新版本

Disk Files and Blocks

- Databases normally read and write disk files in blocks
  - Block-size is usually a power of 2, between 2^9 and 2^{16}
- Main reason is performance:
  - Disk access latency is large, but throughput is also large
  - Accessing 4KiB is just as expensive as accessing one byte
- Also makes it easier for Storage Manager to manage buffering, transactions, etc.
  - Disk pages are a convenient unit of data to work with
- The OS presents files as a contiguous array of bytes…
  - Typically want the database block size to be some multiple of the storage device block size

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磁盘文件和块

数据库通常以块为单位读写磁盘文件
块大小通常是2的幂，介于29和216之间

主要原因是性能：
磁盘访问延迟大，但吞吐量也大
访问4KiB与访问一个字节一样昂贵

还使StorageManager更易于管理
缓冲、交易等
磁盘页是一种方便使用的数据单元

操作系统将文件显示为连续的字节数组……
通常希望数据库块大小是
存储设备块大小

Disk Files and Blocks (2)

- Blocks in a file are numbered starting at 0
- To read or write a block in a data file:
  - Seek to the location *block_num* × *page_size*
  - Read or write *page_size* bytes
- To create a new block:
  - Most platforms will automatically extend a file's size when a write occurs past the end of the file
  - Seek to location of new block, then write new block's data
- To remove blocks from the end of the file:
  - Set the file's size to the desired size
  - File will be truncated (or extended) to the specified size

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磁盘文件和块(2)

文件中的块从0开始编号读取或写入数据文件中的块：

寻找位置block_num×page_size

读取或写入page_size字节

创建一个新块：

大多数平台会自动扩展文件的大小
写入发生在文件末尾之后

寻找新区块的位置，然后写入新区块的数据

从文件末尾删除块：

将文件大小设置为所需大小

文件将被截断（或扩展）到指定的大小

Files and Blocks… and Tuples?

- Issue:
  - Physical data file will be accessed in units of blocks
  - Query engine accesses data as sequences of records, often specifying predicates that the records must satisfy

- How do we organize blocks within data files?
- How do we organize records within blocks?
- Do we want to apply any file-level organization of records as well?

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文件和块……还有元组?

- Issue:

  物理数据文件将以块为单位访问

  查询引擎以记录序列的形式访问数据，
  经常指定记录必须满足的谓词

我们如何在数据文件中组织块?

我们如何在块内组织记录？我们是否要应用任何文件级组织
也有记录?

Caveats

- Two important caveats to state up front:
- Caveat 1 (as before):
  - Most of our discussion going forward will assume spinning magnetic disks, not solid state drives
  - Data is frequently changed in-place
- Caveat 2:
  - We are discussing general implementation approaches, not theory, so there are many “right” ways to do things
  - Most implementations use these approaches, and/or minor variations on them

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Caveats

预先声明的两个重要警告：

- Caveat 1 (as before):

  我们接下来的大部分讨论将假设
  旋转磁盘，而不是固态驱动器

  数据经常就地更改

- Caveat 2:

  我们正在讨论一般的实施方法，
  不是理论，所以有很多“正确”的做事方式

  大多数实现都使用这些方法，并且或
  它们的细微变化

Data File Organization

- Simplification 1:
  - We will store each table's data in a separate file.

- Some databases allow records from related tables to be stored together in a single file
  - e.g. records that would equijoin together are stored adjacent to each other in the file
  - Called a *multitable clustering file organization*
  - Facilitates *very* fast joins between these tables

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数据文件组织

- Simplification 1:
  我们会将每个表的数据存储在单独的文件中。

一些数据库允许将相关表中的记录
一起存储在一个文件中

例如将等值连接在一起的记录被存储
在文件中彼此相邻

称为多表集群文件组织

促进这些表之间的快速连接

Data File Organization (2)

- Simplification 2:
  - We will require that every tuple fits entirely within a single disk block.

- Disk blocks can usually hold multiple records, but it is easy for a tuple to exceed the size of a single block
  - e.g. table with **`VARCHAR(20000)`** field; pg. size of 4KiB
- Most DBs support records larger than a disk block
  - DB can support records that span multiple blocks, or it can use separate overflow storage for large records, etc.

数据文件组织(2)

- Simplification 2:

  我们将要求每个元组完全适合
  单个磁盘块。

磁盘块通常可以容纳多条记录，但它是
元组容易超过单个块的大小

例如带有VARCHAR(20000)字段的表；pg。4KiB大小

大多数数据库支持大于磁盘块的记录

DB可以支持跨越多个块的记录，或者它
可以对大的记录等使用单独的溢出存储。

Considerations

- Operations performed on table data:
  - Inserting new records
    - *(reuse available space before increasing file size?)*
  - Deleting records
    - *(coalesce freed space if possible?)*
  - Selecting/scanning records (possibly applying updates)
  - Operations may involve only a few records, or they may involve many records

- Want to optimally handle the expected usage
  - Evaluate storage format against all above operations!
  - Don't impose too much space overhead
  - Don't unnecessarily hinder speed of operation

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Considerations

对表数据执行的操作：

插入新记录

（在增加文件大小之前重用可用空间？）

删除记录

（如果可能，合并释放的空间？）

选择扫描记录（可能应用更新）操作可能只涉及几条记录，或者它们可能
涉及许多记录

希望以最佳方式处理预期使用情况

针对上述所有操作评估存储格式！不要在开销上施加
太多空间不要不必要地影响操作速度

Example: Inserting Records

- User executes this SQL:

```
INSERT INTO users VALUES
  (103921, 'joebob', 'Joe Bob', 'https://…');
```

- Database must find a block with enough space to hold the new record
- NanoDB's solution:
  - Starting with first data block in table file, search linearly until a block is found with enough space to hold the record
  - If we reach the end of the file, extend the file with a new block and add the record there
- What is this approach good at? What is it bad at?

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示例：插入记录

用户执行以下SQL：

```
插入用户价值
  (103921, 'joebob', 'Joe Bob', 'https://…');
```

数据库必须找到一个有足够空间的块来容纳新纪录

- NanoDB's solution:

从表文件中的第一个数据块开始，线性搜索直到找到一个有足够空间来保存记录的块

如果我们到达文件的末尾，用一个新块扩展文件并在那里添加记录

这种方法擅长什么？它不擅长什么？

Example: Inserting Records (2)

- NanoDB approach is very slow for inserting records!
  - One benefit: reuses free space as much as possible
- Could remember the last block in the file with free space, and start there when adding new rows
- Can also use block-level structures to manage the file
  - Often focused on making it much faster/easier to find available space in the file
- Can also impact database performance if the approach causes many extra disk seeks and/or block reads

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示例：插入记录(2)

NanoDB方法插入记录非常慢！

一个好处：尽可能多地重复使用可用空间

可以用free记住文件中的最后一个块空间，并在添加新行时从那里开始

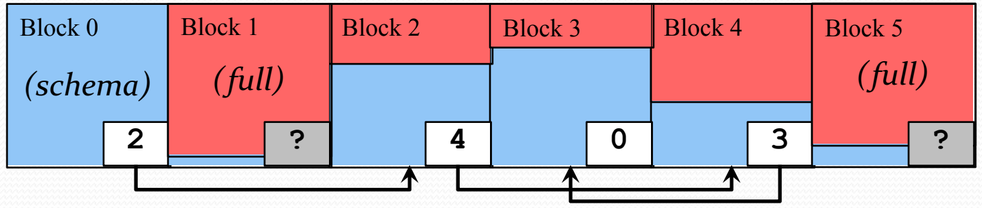
也可以使用块级结构来管理文件

通常专注于使其更快更容易找到文件中的可用空间

如果采用这种方法，也会影响数据库性能导致许多额外的磁盘寻道和/或阻塞读取

Block-Level Organization

- Introduce block-level structure to manage the file
- Example: list of blocks that can hold another tuple
  - First block in the data file specifies start of list
  - "Pointers" in the linked list are simply block numbers
    - e.g. could use a block number of 0 to terminate the list



- In NanoDB, block 0 is special:
  - It holds the table-file's schema, among other things

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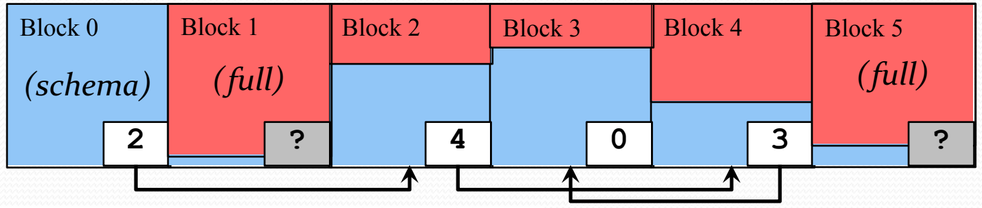
Block-Level Organization

引入块级结构来管理文件示例：可以容纳另一个元组的块列表

数据文件中的第一个块指定链表的开始链表中的"指针"只是块号

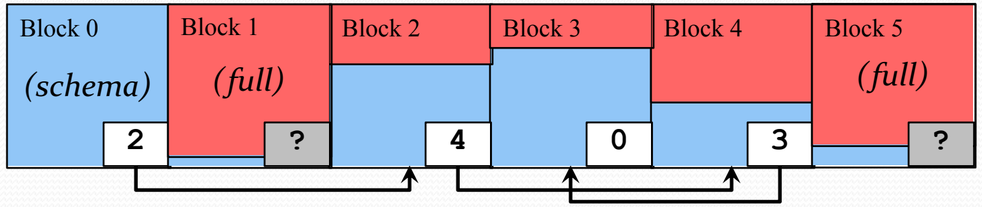
例如可以使用块号0来终止列表



在NanoDB中，块0是特殊的：

它包含表文件的模式，除其他外

List of Non-Full Blocks (1)



- Note that pages will almost never be *completely* full
  - List simply specifies pages that can hold another tuple
- Can use the table's schema to compute minimum and maximum size of a tuple for that table

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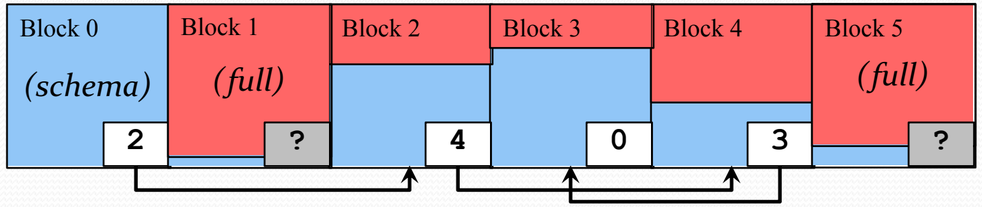
非完整区块列表(1)

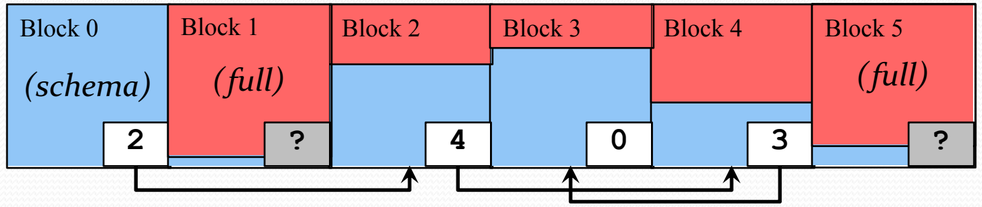


请注意，页面几乎永远不会完全填满

List只是指定可以容纳另一个元组的页面

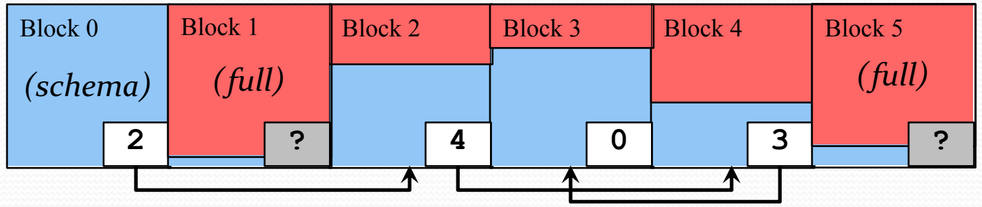
可以使用表的模式来计算最小值和
该表的元组的最大大小

List of Non-Full Blocks (2)



- When a new row is inserted:
  - Starting with first block, search through list of blocks with free space, for space to store the new tuple
  - When space is found, store the tuple
  - If the block is now full, remove it from the list
- Now we sometimes modify *two* pages instead of one

非完整区块列表(2)



插入新行时：

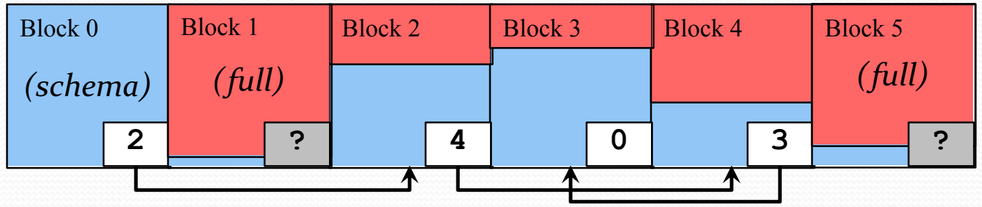
从第一个块开始，搜索块列表
有空闲空间，用于存储新元组的空间

找到空间后，存储元组

如果块现在已满，请将其从列表中删除

现在我们有时会修改两页而不是一页

List of Non-Full Blocks (3)



- When a new row is inserted:
  - Starting with first block, search through list of non-full blocks for space to store the new tuple
- Other performance issues?
  - Scanning through the list of non-full blocks will likely incur many disk seeks
  - Could mitigate this by keeping free list in sorted order, but this would be more expensive to maintain

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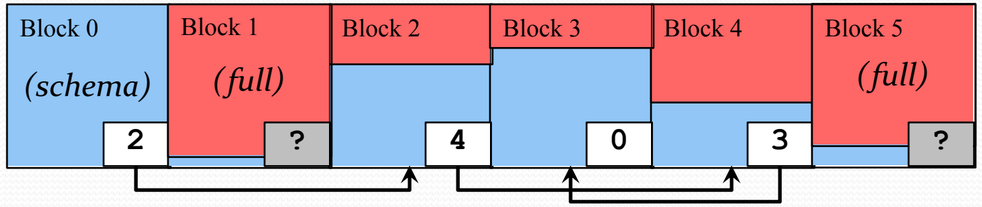
非完整区块列表(3)



插入新行时：

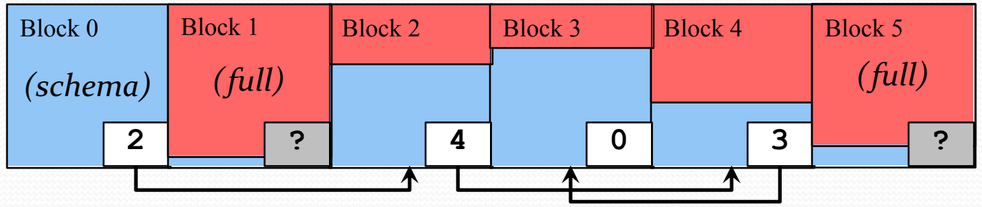
从第一个块开始，搜索非完整块列表
用于存储新元组的空间

其他性能问题?

扫描非完整块列表可能会导致
许多磁盘寻道

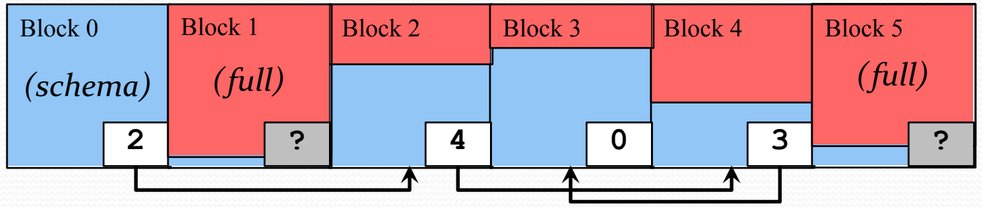
可以通过保持空闲列表排序来缓解这种情况，但是
这将更加昂贵

List of Non-Full Blocks (4)



- When a row is deleted:
  - If block was previously full, need to add it to the non-full list
    - e.g. if tuple was deleted from block 5
  - A simple solution: always add the block to start of the list
    - (Issue: Non-full list will become out of order)
  - Again, two blocks are written in some situations
  - (It's likely that block 0 will already be in cache, though)

非完整区块列表(4)



当一行被删除时：

如果块之前已满，则需要将其添加到未满列表中

例如如果元组从块5中删除

一个简单的解决方案：总是将块添加到列表的开头

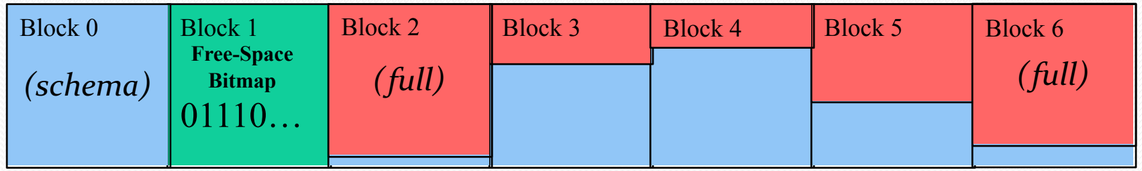
（问题：非完整列表将变得乱序）

同样，在某些情况下会写入两个块

（不过，块0很可能已经在缓存中）

Free-Space Bitmap

- Can also use a *free-space bitmap* to record blocks with available space
  - 0 = “block is full”
  - 1 = “block may have room for another tuple”



- Achieves same benefits as a list of non-full blocks, but with far fewer seeks, less space consumed, etc.
  - Requires same operations as non-full list, but they all operate on the free-space bitmap
  - Can become a performance bottleneck w/concurrent writes

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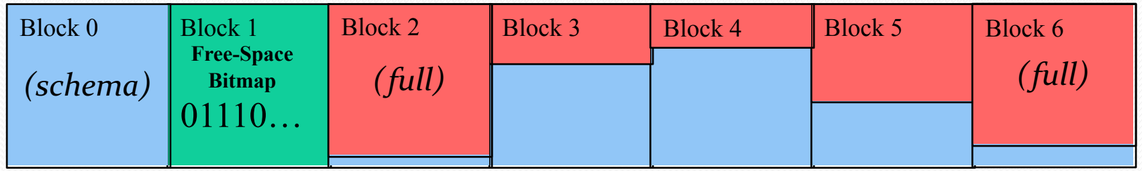
Free-Space Bitmap

也可以使用自由空间位图来记录块
可用空间
0=“块已满”1=“块可能有空间容纳另一个元组”



实现与非完整块列表相同的好处，但具有
更少的搜索，更少的空间消耗等。
需要与非完整列表相同的操作，但它们都可以操作
在自由空间位图上
并发写入可能成为性能瓶颈