15. Concurrent Disks and Directories

In this handout we give examples of more elaborate concurrent programs:

> An implementation of `Disk.read` using the same kind of caching used in `BufferedDisk` from handout 7 on file systems, but now with concurrent clients.
>
> An implementation of a directory tree or graph, as discussed in handout 12 on naming, but again with concurrent clients.

Concurrent buffered disk

The `ConcurrentDisk` module below is similar to `BufferedDisk` in handout 7 on file systems; both implement the `Disk` spec. For simplicity, we omit the complications of crashes. As in handout 7, the buffered disk is based on an underlying implementation of `Disk` called `UDisk`, and calls on `UDisk` routines are in bold so you can pick them out easily.

We add a level of indirection so that we can have names (called `B`'s) for the buffers; a `B` is just an integer, and we keep the buffers in a sequence called `bv`. `B` has methods that let us write `b.db` for `bv(b).db` and similarly for other fields.

The `cache` is protected by a mutex `mc`. Each cache buffer is protected by a mutex `b.m`; when this is held, we say that the buffer is *locked*. Each buffer also has a count `users` of the number of `b`'s to the buffer that are outstanding. This count is also protected by `mc`. It plays roughly the role of a readers lock on the cache reference to the buffer during a disk transfer; if it's non-zero, it is not OK to reassign the buffer to a different disk page. `GetBufs` increments `users`, and `InstallData` decrements it. No one waits explicitly for this lock. Instead, `read` just waits on the condition `moreSpace` for more space to become available.

Thus there are three levels of locking, allowing successively more concurrency and held for longer times:

> `mc` is global, but is held only during pointer manipulations;
>
> `b.m` is per buffer, but exclusive, and is held during data transfers;
>
> `b.users` is per buffer and shared; it keeps the assignment of a buffer to a `DA` from changing.

There are three design criteria for the implementation:

1. Don't hold `mc` during an expensive operation (a disk access or a block copy).
2. Don't deadlock.
3. Handle additional threads that want to read a block being read from the disk.

You can check by inspection that the first is satisfied. As you know, the simple way to ensure the second is to define a partial order on the locks, and check that you only acquire a lock when it is greater than one you already have. In this case the order is `mc` < every `b.m`. The `users` count takes care of the third.

The loop in `read` calls `GetBufs` to get space for blocks that have to be read from the disk (this work was done by `MakeCacheSpace` in handout 7). `GetBufs` may not find enough free buffers, in which case it returns an empty set to `read`, which waits on `moreSpace`. This condition is signaled by the demon thread `FlushBuf`. A real system would have signaling in the other direction too, from `GetBufs` to `FlushBuf`, to trigger flushing when the number of clean buffers drops below some threshold.

The boxes in `ConcurrentDisk` highlight places where it differs from `BufferedDisk`. These are only highlights, however, since the code differs in many details.

```
CLASS ConcurrentDisk EXPORT read, write, size, check, sync =

TYPE
    % Data, DA, DB, Blocks, Dsk, E as in Disk
    I           =  Int
    J           =  Int

    Buf         =  [db, m, users: I, clean: Bool]     % m protects db, mc the rest
    M           =  Mutex
    B           =  Int WITH {m    :=(\b|bv(b).m),     % index in bv
                             db   :=(\b|bv(b).db),
                             users:=(\b|bv(b).users),
                             clean:=(\b|bv(b).clean)}
    BS          =  SET B

CONST
    DBSize      := Disk.DBSize
    nBufs       := 100
    minDiskRead := 5                                  % wait for this many Bufs

VAR
    % uses UDisk's disk, so there's no state for that
    udisk       :  Disk
    cache       := (DA -> B){}                        % protected by mc
    mc          :  M                                  % protects cache, users
    moreSpace   :  Condition.C                        % wait for more space
    bv          :  (B -> Buf)                         % see Buf for protection
    flushing    :  (DA + Null) := nil                 % only for the AF

% ABSTRACTION FUNCTION Disk.disk(0) = (\ da |
    (    cache!da /\ (cache(da).m not held \/ da = flushing) => cache(da).db
     [*] UDisk.disk(0)(da) ))
```

The following invariants capture the reasons why this code works. They are not strong enough for a formal proof of correctness.

```
% INVARIANT 1: ( ALL da :IN cache.dom, b |
    b = cache(da) /\ b.m not held /\ b.clean ==> b.db = UDisk.disk(0)(da) )
```

A buffer in the cache, not locked, and clean agrees with the disk (if it's locked, the code in `FlushBuf` and the caller of `GetBufs` is responsible for keeping track of whether it agrees with the disk).

```
% INVARIANT 2: (ALL b | {da | cache!da /\ cache(da) = b}.size <= 1)
```

A buffer is in the cache at most once.

```
% INVARIANT 3: mc not held ==> (ALL b :IN bv.dom | b.clean /\ b.users = 0
                                                  ==> b.m not held)
```

If `mc` is not held, a clean buffer with `users = 0` isn't locked.

```
PROC new(size: Int) -> Disk =
    self := StdNew(); udisk := udisk.new(size);
    mc.acq; DO VAR b | ~ bv!b => VAR m := m.new() |
        bv(b) := Buf{m := m, db := {}, users := 0, clean := true}
    OD; mc.rel
    RET self

PROC read(e) -> Data RAISES {notThere} =
    udisk.check(e);
    VAR data := Data{}, da := e.da, upto := da + e.size, i |
        mc.acq;
        % Note that we release mc before a slow operation (bold below)
        % and reacquire it afterward.
        DO da < upTo => VAR b, bs |                 % read all the blocks
            IF  cache!da =>
                b := cache(da);                     % yes, in buffer b; copy it
                % Must increment users before releasing mc.
                bv(b).users + := 1; mc.rel;
                % Now acquire m before copying the data.
                % May have to wait for m if the block is being read.
                b.m.acq; data + := b.db; b.m.rel;
                mc.acq; bv(b).users - := 1;
                da := da + 1
             [*] i := RunNotInCache(da, upTo);      % da not in the cache
                bs := GetBufs(da, i); i := bs.size; % GetBufs is fast
                IF  i > 0 =>
                    mc.rel; data + := InstallData(da, i); mc.acq;
                    da + := i
                [*] moreSpace.wait(mc)
                FI
            FI
        OD; mc.rel; RET data

FUNC RunNotInCache(da, upTo: DA) -> I =             % mc locked
    RET {i | da + i <= upTo /\ (ALL j :IN i.seq | ~ cache!(da + j))).max
```

`GetBufs` tries to return `i` buffers, but it returns at least `minDiskRead` buffers (unless `i` is less than this) so that `read` won't do lots of tiny disk transfers. It's tempting to make `GetBufs` always succeed, but this means that it must do a `Wait` if there's not enough space. While `mc` is released in the `Wait`, the state of the cache can change so that we no longer want to read `i` pages. So the choice of `i` must be made again after the `Wait`, and it's most natural to do the `Wait` in `read`.

If `users` and `clean` were protected by `m` (as `db` is) rather than by `mc`, `GetBufs` would have to acquire pages one at a time, since it would have to acquire the `m` to check the other fields. If it couldn't find enough pages, it would have to back out. This would be both slow and clumsy.

```
PROC GetBufs(da, i) -> BS =
% mc locked. Return some buffers assigned to da, da+1, ..., locked, and
% with users = 1, or {} if there's not enough space. No slow operations.
  VAR bs := {b | b.users = 0 /\ b.clean} |                  % the usable buffers
    IF   bs.size >= {i, minDiskRead}.min =>                  % check for enough buffers
         i := {i, bs.size}.min;
         DO VAR b | b IN bs /\ b.users = 0 =>
             % Remove the buffer from the cache if it's there.
             IF VAR da' | cache(da') = b => cache := cache{da' -> } [*] SKIP FI;
             b.m.acq; bv(b).users := 1; cache(da) := b; da + := 1
         OD; RET {b :IN bs | b.users > 0}
    [*]  RET {}                                              % too few; caller must wait
    FI
```

In handout 7, `InstallData` is done inline in `read`.

```
PROC InstallData(da, i) = VAR data, j := 0 |
% Pre: cache(da) .. cache(da+i-1) locked by SELF with users > 0.
    data := udisk.read(E{da, i});
    DO j < i => VAR b := cache(da + j) |
        bv(b).db := udisk.DToB(data).sub(j); b.m.rel;
        mc.acq; bv(b).users - := 1; mc.rel;
        j + := 1
    OD; RET data
```

`PROC write` is omitted. It sets `clean` to `false` for each block it writes. The background thread `FlushBuf` does the writes to disk. Here is a simplified version that does not preserve write order. Note that, like `read`, it releases `mc` during a slow operation.

```
THREAD FlushBuf() = DO                                      % flush a dirty buffer
    mc.acq;
    IF  VAR da, b | b = cache(da) /\ b.users = 0 /\ ~ b.clean =>
        flushing := true;                                    % just for the AF
        b.m.acq; bv(b).clean := true; mc.rel;
        udisk.write(da, b.db);
        flushing := false;
        b.m.rel; moreSpace.signal
     [*] mc.rel
    OD

% Other procedures omitted

END ConcurrentDisk
```

Concurrent directory operations

In handout 12 on naming we gave an `ObjNames` spec for looking up path names in a tree of graph of directories. Here are the types and state from `ObjNames`:

```
TYPE D          =  Int                                 % Just an internal name
                   WITH {get:=GetFromS, set:=SetInS}   % get returns nil if undefined
     Link       =  [d: (D + Null), pn]                 % d=nil means the containing D
     Z          =  (V + D + Link + Null)               % nil means undefined
     DD         =  N -> Z

CONST
     root       :  D := 0
     s          := (D -> DD){}{root -> DD{}}           % initially empty root

APROC GetFromS(d, n) -> Z =                            % d.get(n)
     << RET s(d)(n) [*] RET nil >>

APROC SetInS  (d, n, z)   =                            % d.set(n, z)
% If z = nil, SetInS leaves n undefined in s(d).
     << IF z # nil => s(d)(n) := z [*] s(d) := s(d){n -> } FI >>
```

We wrote the spec to allow the bindings of names to change during lookups, but it never reuses a `D` value or an entry in `s`. If it did, a lookup of `/a/b` might obtain the `D` for `/a`, say `dA`, and then `/a` might be deleted and `dA` reused for some entirely different directory. When the lookup continues it will look for `b` in that directory. This is definitely not what we have in mind.

An implementation, however, will represent a `DD` by some data structure on disk (and cached in RAM), and if the directory is deleted it will reuse the space. This code needs to prevent the anomalous behavior we just described. The simplest way to do so is similar to the `users` device in `ConcurrentDisk` above: a shared lock that prevents the directory data structure from being deleted or reused.

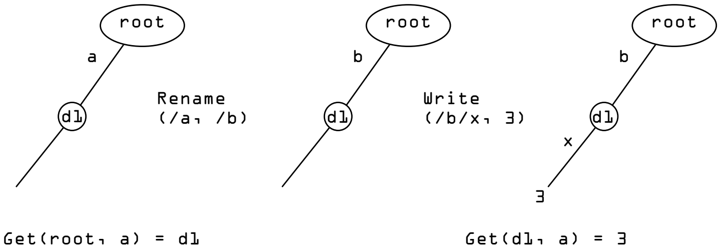
The situation is trickier here, however. It's necessary to make sufficiently atomic the steps of first looking up `a` to obtain `dA`, and then incrementing `s(dA).users`. To do this, we make `users` a true readers lock, which prevents changes to its directory. In particular, it prevents an entry from being deleted or renamed, and thus prevents a subdirectory from being deleted. Then it's sufficient to hold the lock on `dA`, look up `b` to obtain `dB`, and acquire the lock on `dB` before releasing the lock on `dA`. This is called 'lock coupling'.

As we saw in handout 12, the amount of concurrency allowed there makes it possible for lookups done during renames to produce strange results. For example, `Read(/a/x)` can return `3` even though there was never any instant at which the path name `/a/x` had the value `3`, or indeed was defined at all. We copy the scenario from handout 12. Suppose:

> initially `/a` is the directory `d1` and `/b` is undefined;
>
> initially `x` is undefined in `d1`;
>
> concurrently with `Read(/a/x)` we do `Rename(/a, /b); Write(/b/x, 3)`.

The following sequence of actions yields `Read(/a/x) = 3`:

> In the `Read` , `Get(root, a) = d1`
>
> `Rename(/a, /b)` makes `/a` undefined and `d1` the value of `/b`
>
> `Write(/b/x, 3)` makes `3` the value of `x` in `d1`
>
> In the `Read`, `RET d1.get(x)` returns `3`.



Obviously, whether this possibility is important or not depends on how clients are using the name space.

To avoid this kind of anomaly, it's necessary to hold a read lock on every directory on the path. When the directory graph is cyclic, code that acquires each lock in turn can deadlock. To avoid this deadlock, it's necessary to write more complicated code. Here is the idea.

Define some arbitrary ordering on the directory locks (say based on the numeric value of `D`). When doing a lookup, if you need to acquire a lock that is less than the biggest one you hold, release the bigger locks, acquire the new one, and then repeat the lookup from the point of the first released lock to reacquire the released locks and check that nothing has changed. This may happen repeatedly as you look up the path name.

This can be made more efficient (and more complicated, alas) with a 'tentative' `Acquire` that returns a failure indication rather than waiting if it can't acquire the lock. Then it's only necessary to backtrack when another thread is actually holding a conflicting write lock.