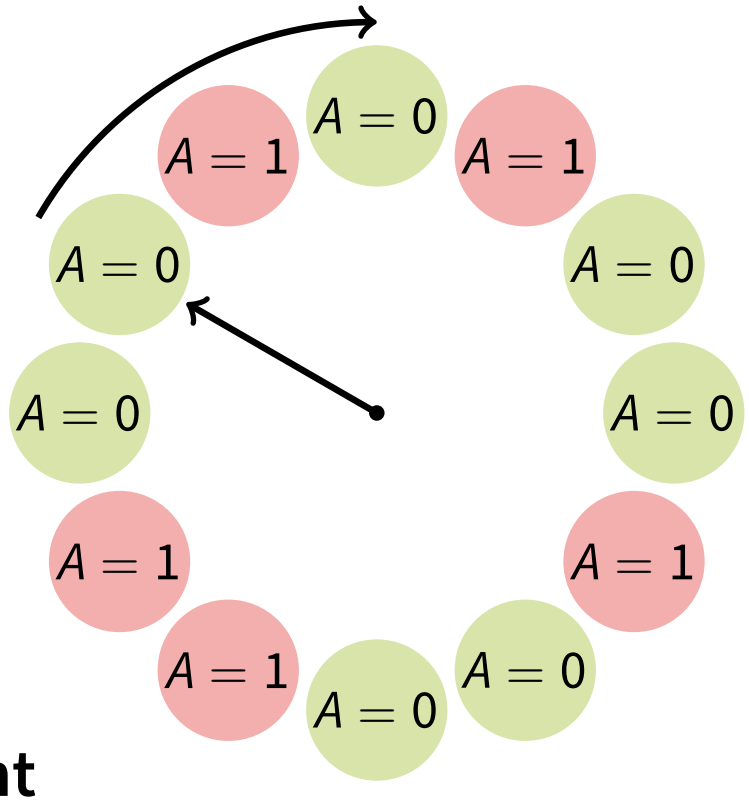
Project 6: Clock Page Replacement

- **Continue to build on code from project 5**
  - No API changes for this project
- **New twist: smaller memory, so `PhysMem::page_alloc` may fail**
  - If no free pages, you must pick an existing `PPage` to *evict*
  - If the page is dirty, you write it back when evicting
  - Use clock algorithm to approximate LRU eviction
- **Why would you want to do this?**
  - Easily add encryption to program (e.g., database) that uses `mmap`
  - Don't want kernel to page out secret plaintext to disk
    - To avoid paging, `PhysMem` uses *locked* physical memory
    - Systems can limit locked mem. (`ulimit -l`)—e.g., 64 MiB on myth (`vm.cc` actually limits locking to 1 MiB to be polite)

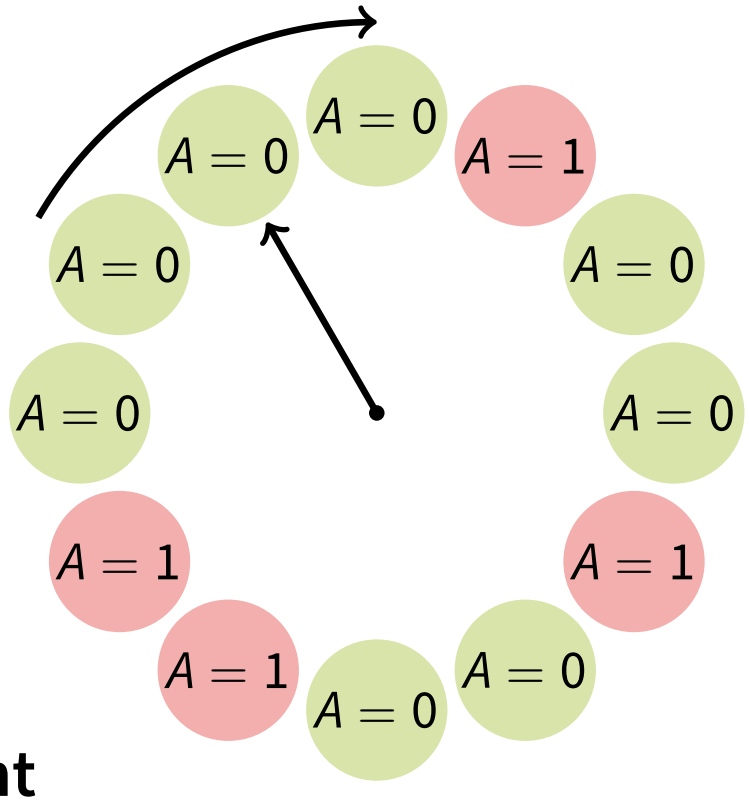
Clock algorithm

- **Idea: evict page that has not been accessed recently**
  - In kernel, would use accessed (A) bit in page table entry (PTE)
  - We will emulate accessed bit by making pages inaccessible
- **Idea: FIFO eviction, but skip accessed pages**
- **Keep pages in circular FIFO list**
- **Scan each physical pages:**
  - → Step "hand" from last evicted
  - Accessed ($A = 1$)? Don't evict, but set $A \leftarrow 0$ (re-map `PROT_NONE`)
  - Not accessed ($A = 0$)? Evict
- **A.k.a. second-chance replacement**



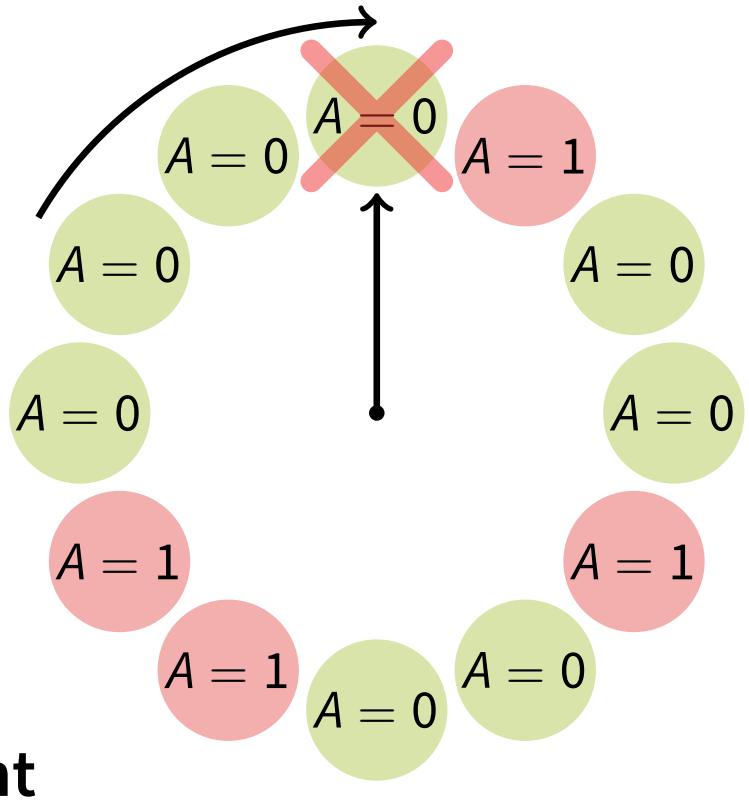
Clock algorithm

- **Idea: evict page that has not been accessed recently**
  - In kernel, would use accessed (A) bit in page table entry (PTE)
  - We will emulate accessed bit by making pages inaccessible
- **Idea: FIFO eviction, but skip accessed pages**
- **Keep pages in circular FIFO list**
- **Scan each physical pages:**
  - Step "hand" from last evicted
  - → Accessed ($A = 1$)? Don't evict, but set $A \leftarrow 0$ (re-map `PROT_NONE`)
  - Not accessed ($A = 0$)? Evict
- **A.k.a. second-chance replacement**

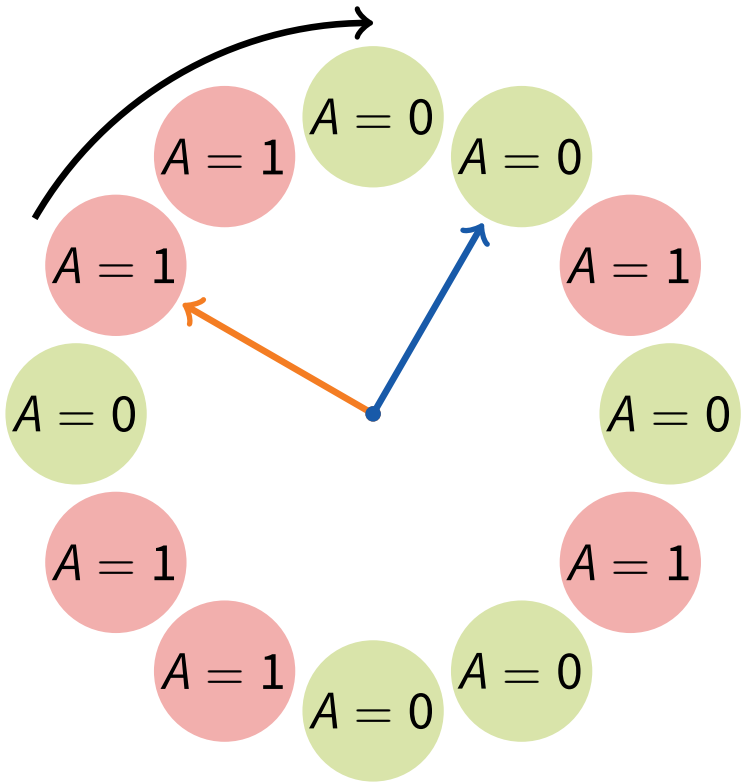


Clock algorithm

- **Idea: evict page that has not been accessed recently**
  - In kernel, would use accessed (A) bit in page table entry (PTE)
  - We will emulate accessed bit by making pages inaccessible
- **Idea: FIFO eviction, but skip accessed pages**
- **Keep pages in circular FIFO list**
- **Scan each physical pages:**
  - Step "hand" from last evicted
  - Accessed ($A = 1$)? Don't evict, but set $A \leftarrow 0$ (re-map `PROT_NONE`)
  - $\longrightarrow$ Not accessed ($A = 0$)? Evict
- **A.k.a. second-chance replacement**

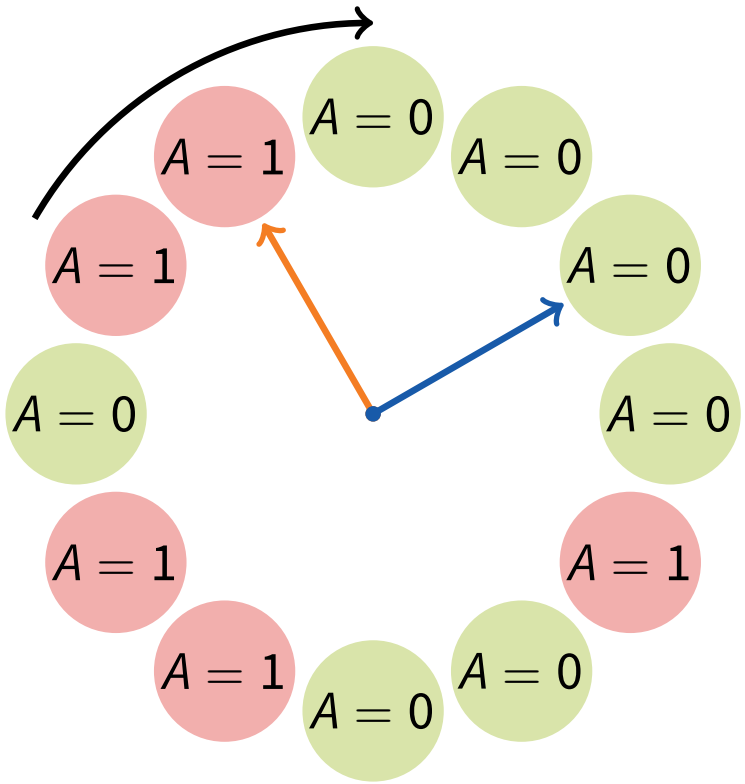


Clock extensions (not for project)



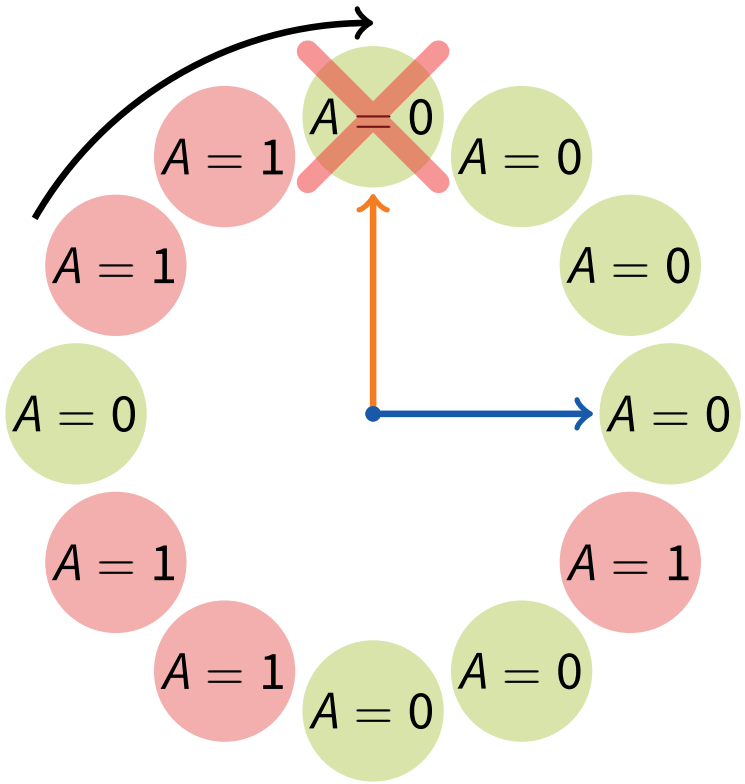
- **Large memory may be a problem**
  - Most pages referenced in long interval
- **Add a second clock hand**
  - Two hands move in lockstep
  - Leading hand clears A bits
  - Trailing hand evicts pages with A=0
- **Can also take advantage of dirty bit**
  - Each page can be (Unaccessed, Clean), (Unaccessed, Dirty), (Accessed, Clean), or (Accessed, Dirty)
  - Consider clean pages for eviction before dirty
- **Or use n-bit accessed *count* instead just A bit**
  - On sweep: $count = (A \ll (n-1)) \mid (count \gg 1)$
  - Evict page with lowest *count*

Clock extensions (not for project)



- **Large memory may be a problem**
  - Most pages referenced in long interval
- **Add a second clock hand**
  - Two hands move in lockstep
  - Leading hand clears A bits
  - Trailing hand evicts pages with A=0
- **Can also take advantage of dirty bit**
  - Each page can be (Unaccessed, Clean), (Unaccessed, Dirty), (Accessed, Clean), or (Accessed, Dirty)
  - Consider clean pages for eviction before dirty
- **Or use n-bit accessed *count* instead just A bit**
  - On sweep: $count = (A \ll (n-1)) \mid (count \gg 1)$
  - Evict page with lowest *count*

Clock extensions (not for project)



- **Large memory may be a problem**
  - Most pages referenced in long interval
- **Add a second clock hand**
  - Two hands move in lockstep
  - Leading hand clears A bits
  - Trailing hand evicts pages with A=0
- **Can also take advantage of dirty bit**
  - Each page can be (Unaccessed, Clean), (Unaccessed, Dirty), (Accessed, Clean), or (Accessed, Dirty)
  - Consider clean pages for eviction before dirty
- **Or use n-bit accessed *count* instead just A bit**
  - On sweep: $count = (A \ll (n-1)) \mid (count \gg 1)$
  - Evict page with lowest *count*

Implementation hints

- **Use a global auxiliary page table, rather than per `MCryptFile`**
  - Page fault in one file may evict page from a different file
  - Global variables often not great for modularity, but here process has only one address space, so a single Aux PT is appropriate
- **Track `PPages` with a `std::vector` the size of `PhysMem`**

```
std::vector<something> frame_table;
    ⋮
  // in set_memory_size:
  frame_table.resize(npages, nullptr);
```

  - *something* could be `VPage`, `AuxPTE*` (as you see fit)
  - Okay, because overhead is a fixed fraction of memory
  - Clock hand is counter mod `npages`
- **Write the `PPage` alias back to disk**
  - With clock, `VPages` will be `PROT_NONE` when evicted
  - Can pass the (always accessible) `PPage` to `aligned_pwrite` instead

C++ container range queries

- **Often want to traverse container elements in range** $[L, H)$
  - Signifies *half-open interval* of all i such that $L \leq i < H$
  - Example: Given `VMRegion *r`, traverse Aux PT entries in the range: [`r->map_base()`, `r->map_base() + r->nbytes_`)
- **Use the** `lower_bound` **method to query range**
  - `c.lower_bound(v)` $\rightarrow$ lowest element $\geq$ `v`, or `end()` if none
  - Start traversal at `container.lower_bound(`L`)`
  - Stop traversal (don't process) `container.lower_bound(`H`)`
- `upper_bound(`H`)` **is end of query for *closed* interval** $[L, H]$
  - First element $> H$ (or `end()` if none)
  - `upper_bound(`H`)-1` is mirror image of `lower_bound(`L`)`
  - If you have duplicate keys, then query half-open interval $[L, H)$ from `lower_bound(`L`)` to `upper_bound(`H`)-1`
- **Demo:** `range.cc`, `dirty.cc` **(corrected)**

C++ lambda `this` captures

- **Capture `this` to make use of current object in a lambda**
  - `[this](){ some_method(); }`
- **Captures the pointer `this`, *not* the object `*this`**
  - Subsequent changes to the object will be reflected in lambda
  - But lambda becomes invalid when object destroyed
- **You probably want to use this technique for page fault handler to capture the current `MCryptFile` object**
- **Can also implicitly capture this with `[&](){...}` or `[=](){...}`**
  - Using `[=]` to capture `this` is a warning as of C++20, so be explicit
- **Demo:** `capture.cc`

C++ exceptions

- **To throw an exception:** `throw e;`
  - `e` can be any type (probably a design mistake in C++)
  - By convention, use only subclasses of `std::exception`, has virtual function `char *what()` for human-readable info
- **Handle exceptions with try, then one or more catch blocks**
  - `catch (const T &t) { ...}` catches anything that is a `T`
  - Only the first matching `catch` block is used
  - Can end with `catch(...)` to catch anything
  - Can re-throw current exception with `throw;` (no `e`)
  - Function-try-block can catch exceptions in initializers
- **When exception escapes scope, destroys all variables**
  - Convenient to avoid resource links
  - But means you shouldn't let exceptions escape destructors
- **Demo:** `throw.cc`

Exceptions vs. returning error

+ **Error handling needs less typing w. exceptions (fewer bugs)**
+ **Only convenient way to return errors from constructors**
+ **Easy to convey extra information in exception**

```
std::unique_ptr<thing> openit();  // OK, no info if NULL
std::string openit(thing *);      // OK, less convenient
// Returning thing and/or error string gets ugly:
std::pair<thing, std::string> openit();
std::variant<thing, std::string> openit();
```

– **Much higher overhead than return value**
  - Don't use as distinguished return value (e.g., item not in set)
– **Makes destructors more brittle**
– **Need some hacks to implement "`finally`"**

• **Demo:** `finally.cc` **(unfinished demo from syncimpl section)**

`mmap` system call

- `void *mmap (void *addr, size_t len, int prot, int flags, int fd, off_t offset)`
  - Map file specified by `fd` at virtual address `addr`
  - If `addr` is NULL, let kernel choose the address
- `prot` – **protection of region**
  - OR of PROT_EXEC, PROT_READ, PROT_WRITE, PROT_NONE
- `flags`
  - MAP_ANON – anonymous memory (`fd` should be -1)
  - MAP_PRIVATE – modifications are private
  - MAP_SHARED – modifications seen by everyone

More VM system calls

- `int msync(void *addr, size_t len, int flags);`
  - Flush changes of mmapped file to backing store
- `int munmap(void *addr, size_t len)`
  - Removes memory-mapped object
- `int mprotect(void *addr, size_t len, int prot)`
  - Changes protection on pages to bitwise or of some `PROT_`...values
- `int mincore(void *addr, size_t len, char *vec)`
  - Returns in `vec` which pages present

Exposing page faults

```
struct sigaction {
  union {                /* signal handler */
    void (*sa_handler)(int); // Normal handler
    // But if you set SA_SIGINFO in sa_flags, can use this:
    void (*sa_sigaction)(int, siginfo_t *, ucontext_t *);
  };
  sigset_t sa_mask;   /* signal mask to apply */
  int sa_flags;
};

int sigaction (int sig, const struct sigaction *act,
               struct sigaction *oact)
```

- **Can specify function to run on `SIGSEGV` (Unix signal raised on invalid memory access)**
  - `siginfo_t::si_addr` is faulting virtual address
  - Even more info in `ucontext_t`
  - Look at `/usr/include/sys/ucontext.h`

How `vm.cc` works

- `PhysMem` **creates a temporary file for physical memory**
  - Can't create aliases for pages created `MAP_ANON`
  - Keeps file descriptor open but immediately deletes file
  - Uses `mmap` to map entire file (at `pool_base()`) with `MAP_SHARED`
- `VMRegion` **maps whole anonymous region with** `PROT_NONE`
  - Reserves virtual addresses, but doesn't change kernel page tables
- `VMRegion::map` **uses** `mmap` **to override on page mapping**
  - Use `PPage` address to get offset in temporary file
  - Re-map `mmap` 4 KiB in file at `VPage` address with requested permissions, creating an alias for same physical page
- `VMRegion::map` **uses** `mmap` **to request 4 KiB anonymous** `PROT_NONE` **at** `VPage`
- **Signal handler gets faulting address from** `siginfo_t`
  - Uses global `itree` to find appropriate `VMRegion` and handler

Lesson: VM tricks not just for the kernel

- **Combination of `mprotect`/`sigaction` very powerful**
  - E.g., fault, unprotect page, return from signal handler
  - Can basically use OS VM tricks in user-level programs
- **Technique used in object-oriented databases**
  - Bring in objects on demand
  - Keep track of which objects may be dirty
  - Manage memory as a cache for much larger object DB
- **Other interesting applications**
  - Useful for some garbage collection algorithms
  - Snapshot processes (copy on write)
- **Classic research paper advocating these techniques: [Appel]**