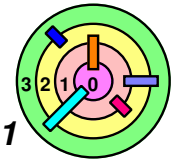
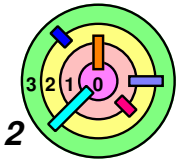
5.3 Scheduling

- *Goals*
- Scheduling Algorithms
- Implementation Issues
- Case Studies



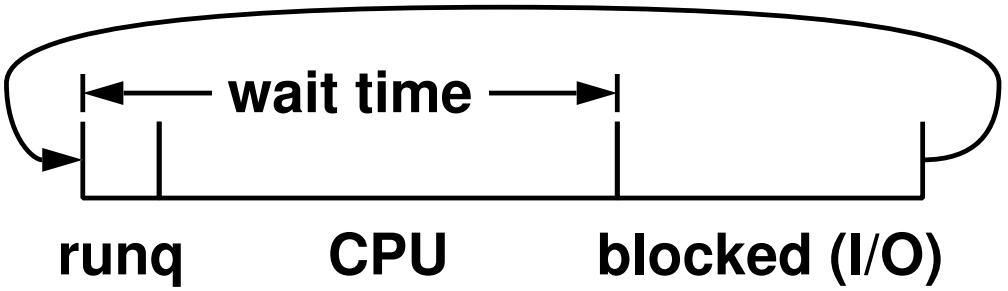
Sample Sorts of Systems

- Simple batch
- Multiprogrammed batch
- Time sharing (i.e., interactive)
- Partitioned servers
- Real time *(i.e., thread must run before a deadline)*
  - *hard real time* (control) vs. *soft real time* (audio/video)
    - for hard real time system, missing deadline means *disaster*
      - e.g., controlling a nuclear power plant, landing (softly) on Mars
      - usually need specialized OS
    - for soft real time system, missing deadline *degrades quality* and user experience
      - e.g., playing streaming audio or video
      - can be supported by general purpose OS these days
- General purpose

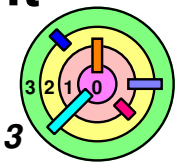


Scheduling

- Goals (some are in conflict with one another)
  - *maximize CPU utilization*
  - *maximize throughput (jobs/sec)*



    - a thread sometimes can be classified as either *CPU-bound* or *I/O-bound*
  - *minimize wait time*
  - *minimize response time* (for interactive and real time applications)
  - *fairness*
    - approximately assign equal proportion of CPU to threads
- Scheduling is very important because its effects and how well it achieves the above goals can be *felt* by the user



5.3 Scheduling

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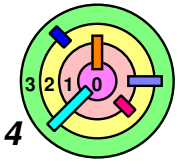
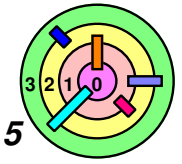


Scheduling Algorithms

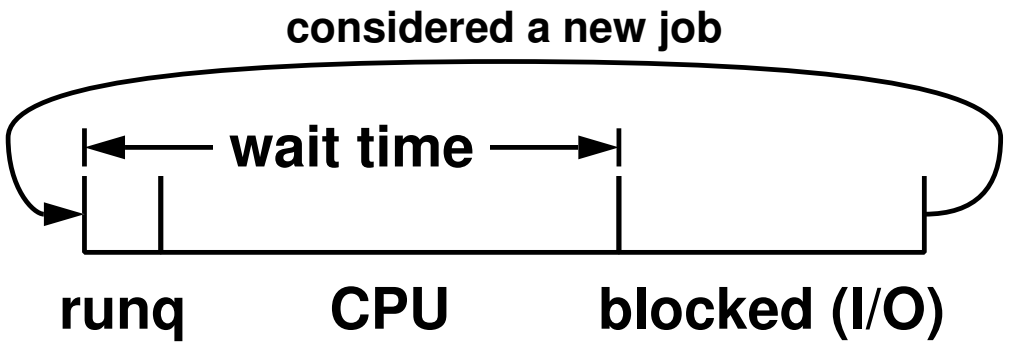
Basic	Priority	Prortional Share	Real Time
FIFO	Multi-level	Lottery	EDF
SJF	Multi-level w/ Feedback*	Stride*	Rate Monotonic
SRTN			
RR			

⇨ We will focus on how the *run queue* is managed



Scheduling Non-preemptive, Non-interactive Jobs

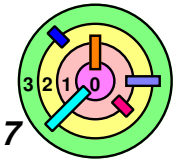
- Scheduling "jobs"



- Run one at a time
  - *no preemption*
- Running time is *known*

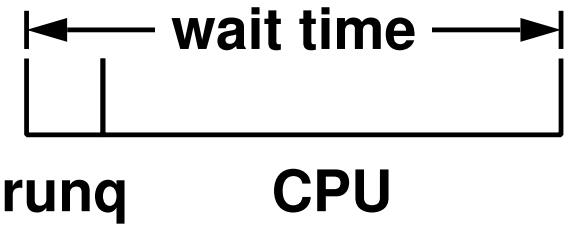
FIFO

- Ex: weenix

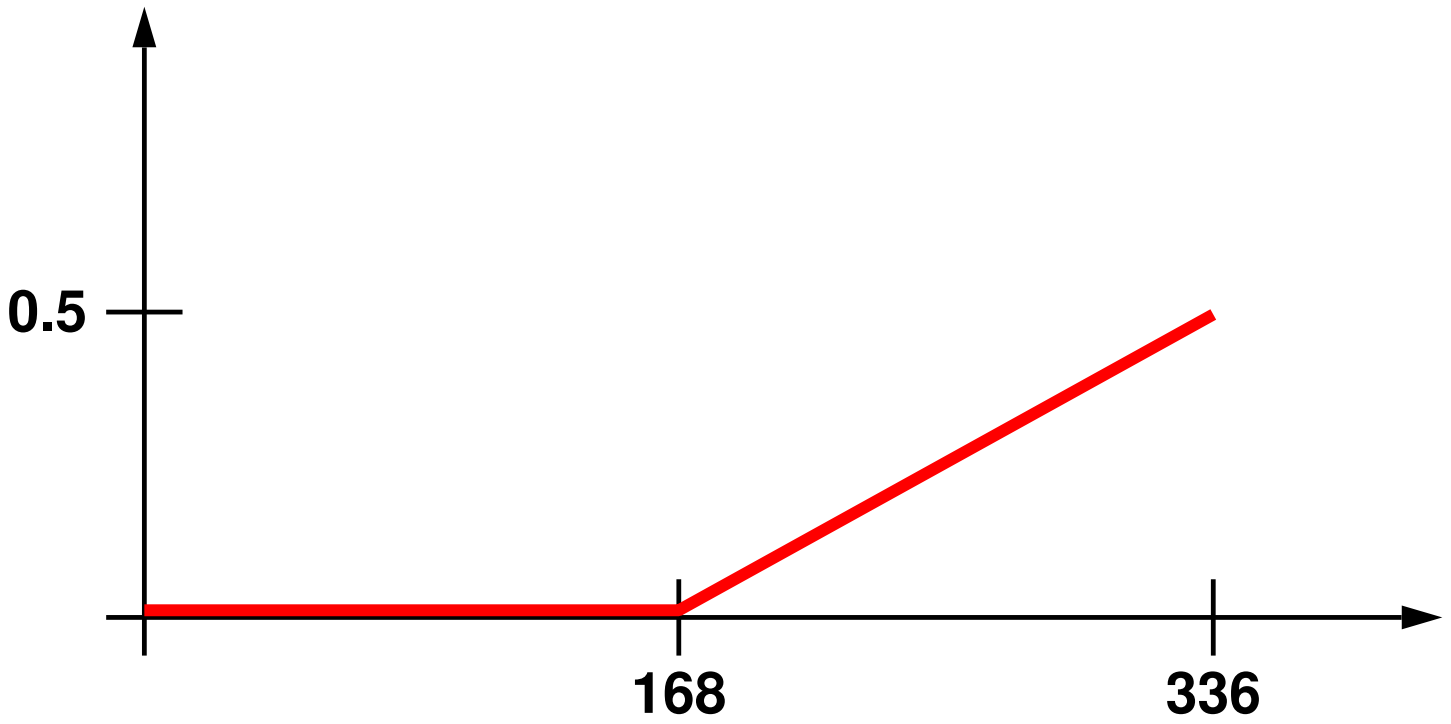


Throughput

- "Goodness" criterion is jobs/hour
  - assuming that all jobs are sitting in the run queue at time 0

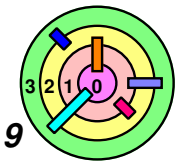


- Ex:
  - one 168-hour job
  - followed by 168 one-hour jobs



Average Wait Time

- Jobs J_i with processing times T_i for $0 \le i < n$
- *Average wait time (AWT)*
  - please note that this is *not* the same "wait time" in warmup #2
  - J_i started at time t_i
  - $t_i = \sum_{j=0}^{i-1} T_j$
  - $AWT = \sum_{i=0}^{n-1} (t_i + T_i) / n$
- For our example
  - AWT = 252 hours (with a standard deviation of 42.25 hours)
    - large average and large variation (for this example)

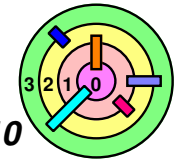


Shortest Job First

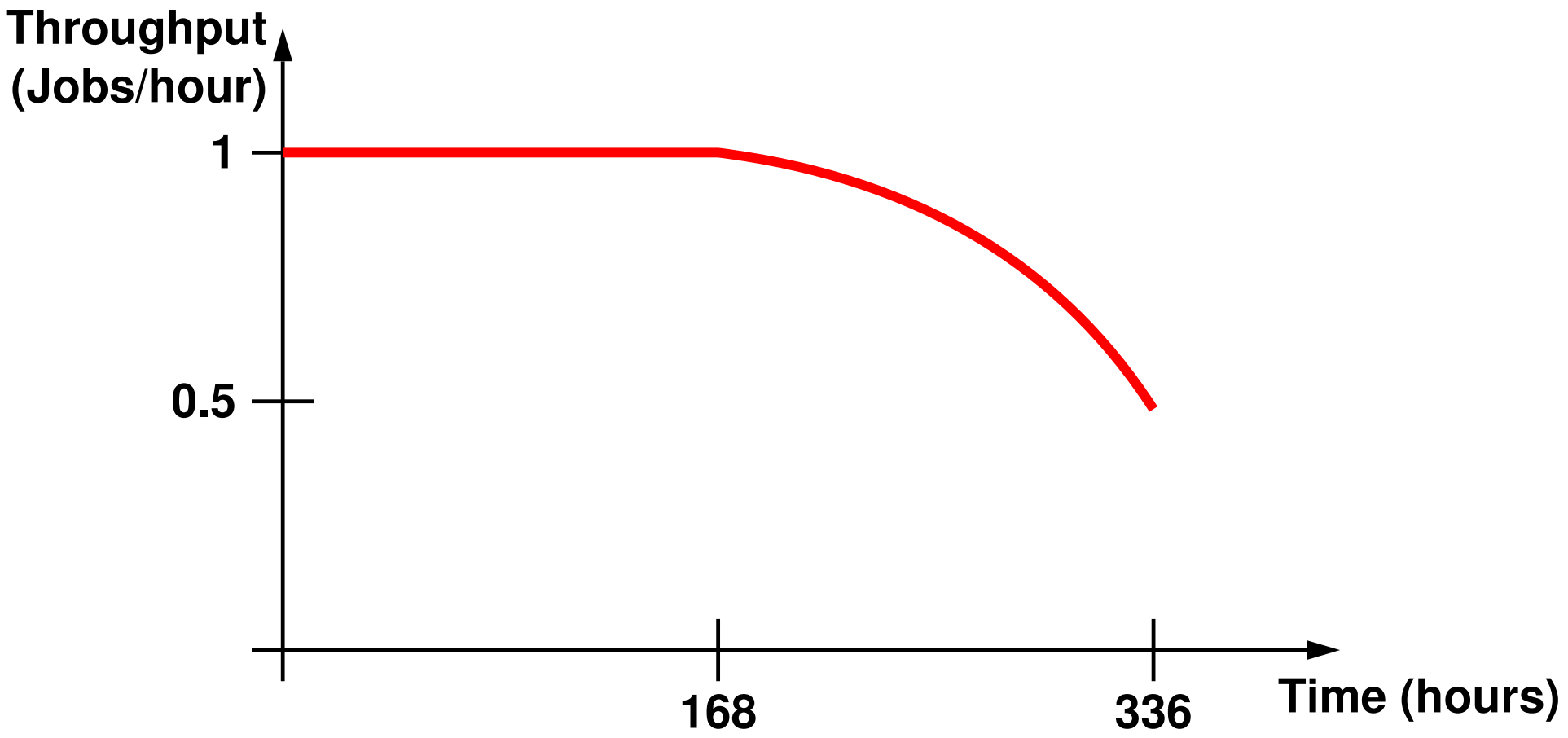
- $AWT = \sum_{i=0}^{n-1} (t_i + T_i) / n$
  - $t_i = \sum_{j=0}^{i-1} T_j$

- $AWT = (nT_0 + (n-1)T_1 + (n-2)T_2 + \ldots + 2T_{n-2} + T_{n-1}) / n$

- Minimized when $T_i \leq T_{i+1}$ for all i
  - which is *Shortest Job First (SJF)*



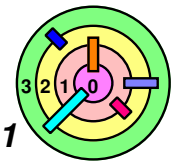
SJF and Our Example



- AWT = 86 hours (with a standard deviation of 52 hours)

⇨ But, what if short jobs keep arriving?

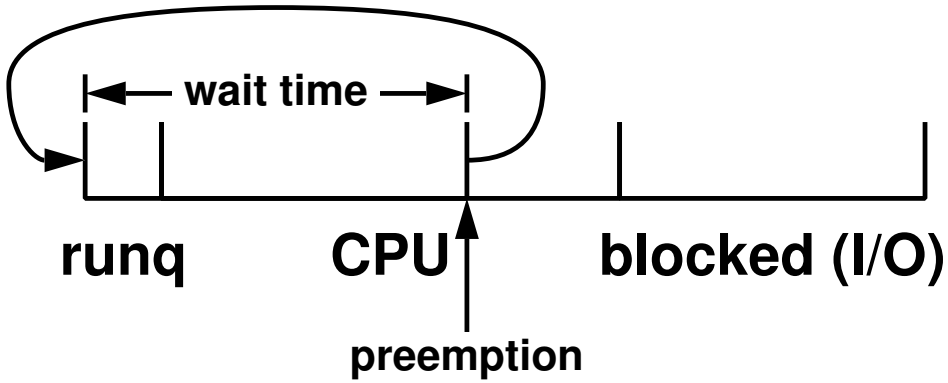
- *starvation*

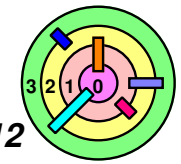


Scheduling Preemptive, Non-interactive Jobs

- ***Preemption:***
  - current job may be preempted by others
    - ***shortest remaining time next (SRTN)***
      - ***optimized throughput***

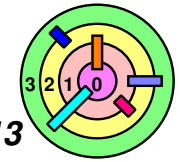
- **Note: we will reserve the term "SJF" to refer to the non-preemptive case**





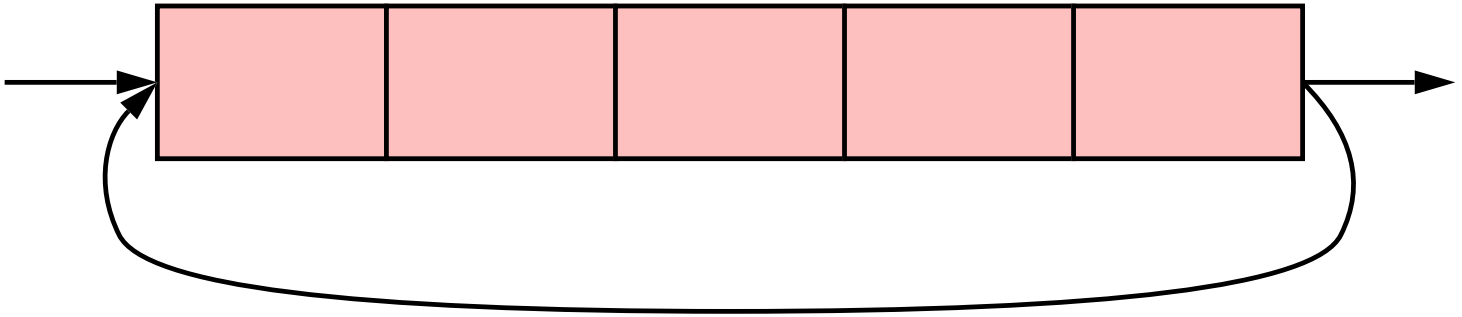
Fairness

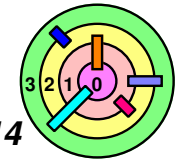
- FIFO
  - each job eventually gets processed
- SJF and SRTN
  - a long job might have to wait indefinitely
- What's a good measure?



Round Robin

- Time-slicing
  - q = quatum / time slice





Round Robin

- Time-slicing
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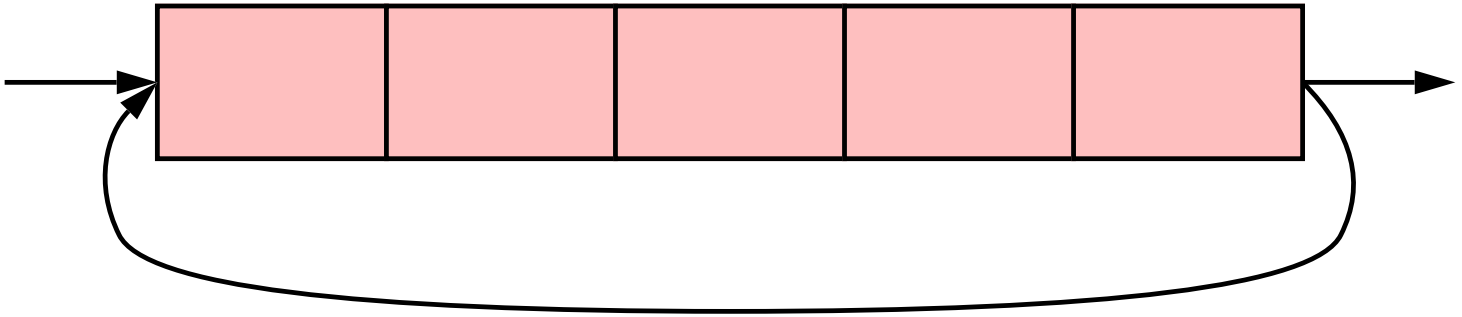
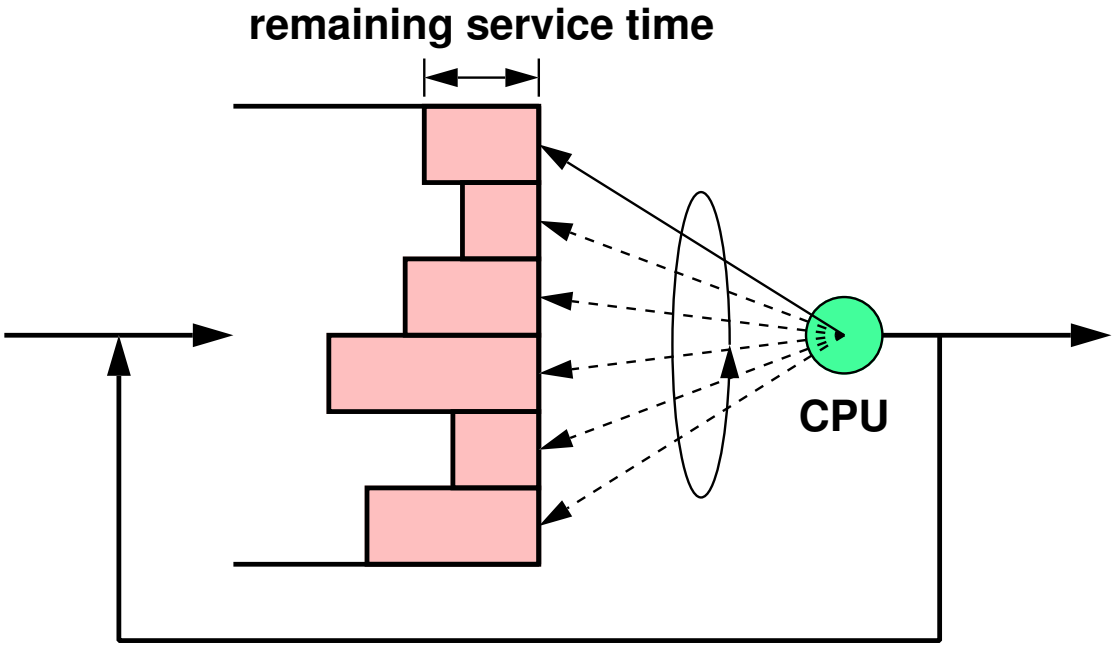
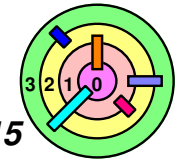
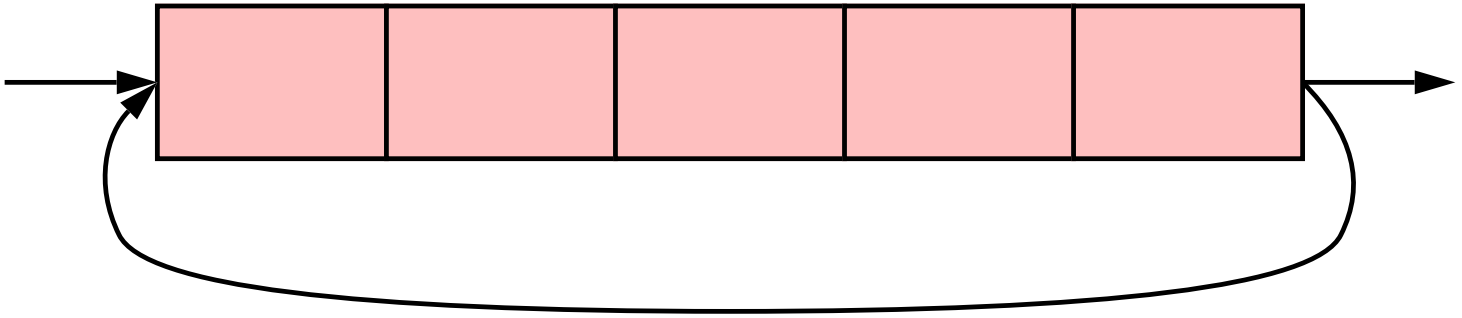




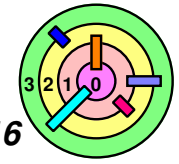


Round Robin

- Time-slicing
  - q = quatum / time slice

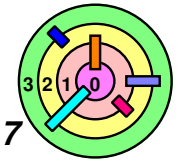


- Different values of q
  - q $\rightarrow$ 0: processor-sharing (idealized case)
    - not realistic
    - *translation lookaside buffer flushing* and *caching problem*
      - not enough time to achieve good hit-rate in TLB
  - q too large: some jobs appear to be not making progress



Round Robin + FIFO

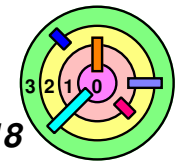
- AWT?
  - let quantum approach 0
  - 169 jobs sharing the processor
  - run at 1/169th speed for first week
  - short jobs receive one hour of processor time in 169 hours
    - different from SJF since all short jobs finish at about the same time
  - long job completes in 336 hours
  - AWT = 169.99 hours
    - recall that AWT is 252 hours for FIFO in our example and 86 hours for SJF
  - *average deviation = 1.96 hours*
    - recall that average deviation = 42.25 hours for FIFO in our example and 52 hours for SJF



Max-min Fairness

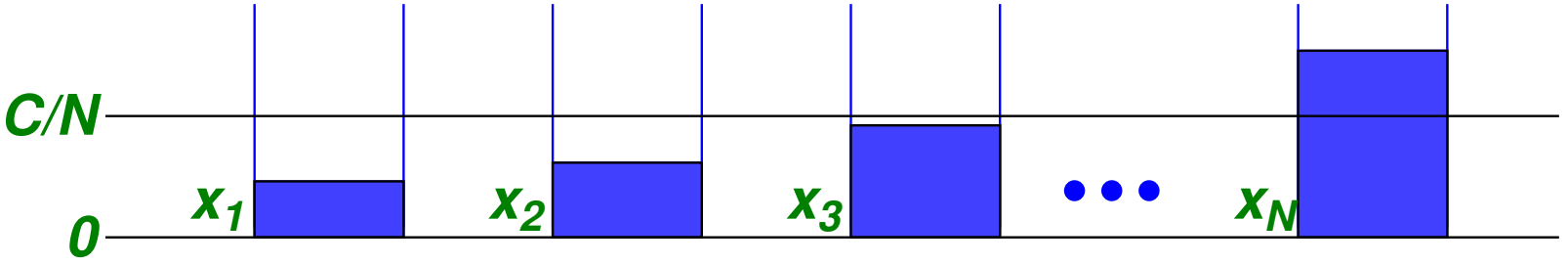
- ***Max-min Fairness:*** **a fair service maximizes the service of the customer receiving the poorest service**

- ***Max-min Fairness* criterion:**
  1) **no user receives more than its *request***
  2) **no other allocation scheme satisfying condition 1 has a high minimum allocation**
  3) **condition 2 remains recursively true as we remove the minimal user and reduce total resource accordingly**

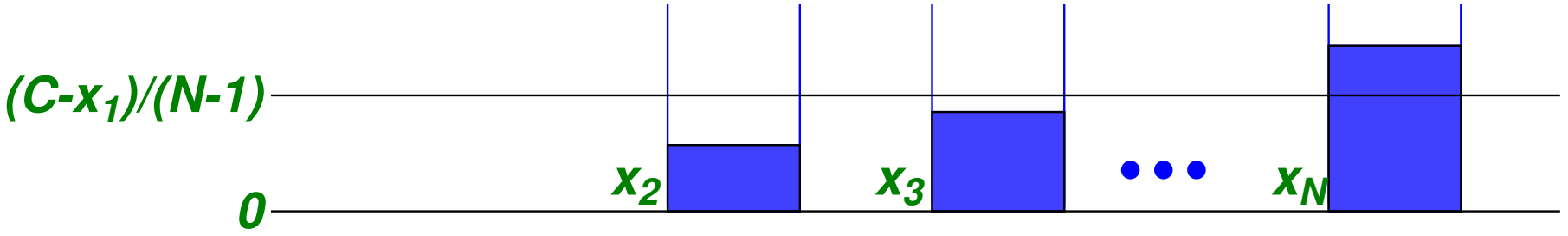


Max-min Fairness Example

- Total capacity *C* divided among *N* jobs
  - x_i is the request of job *i*
  - sort jobs based on x_i
  - initially, assign *C/N* to each job



  - satisfy x_1, redistribute remaining capacity evenly

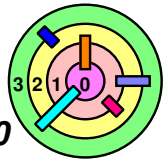


  - recursion

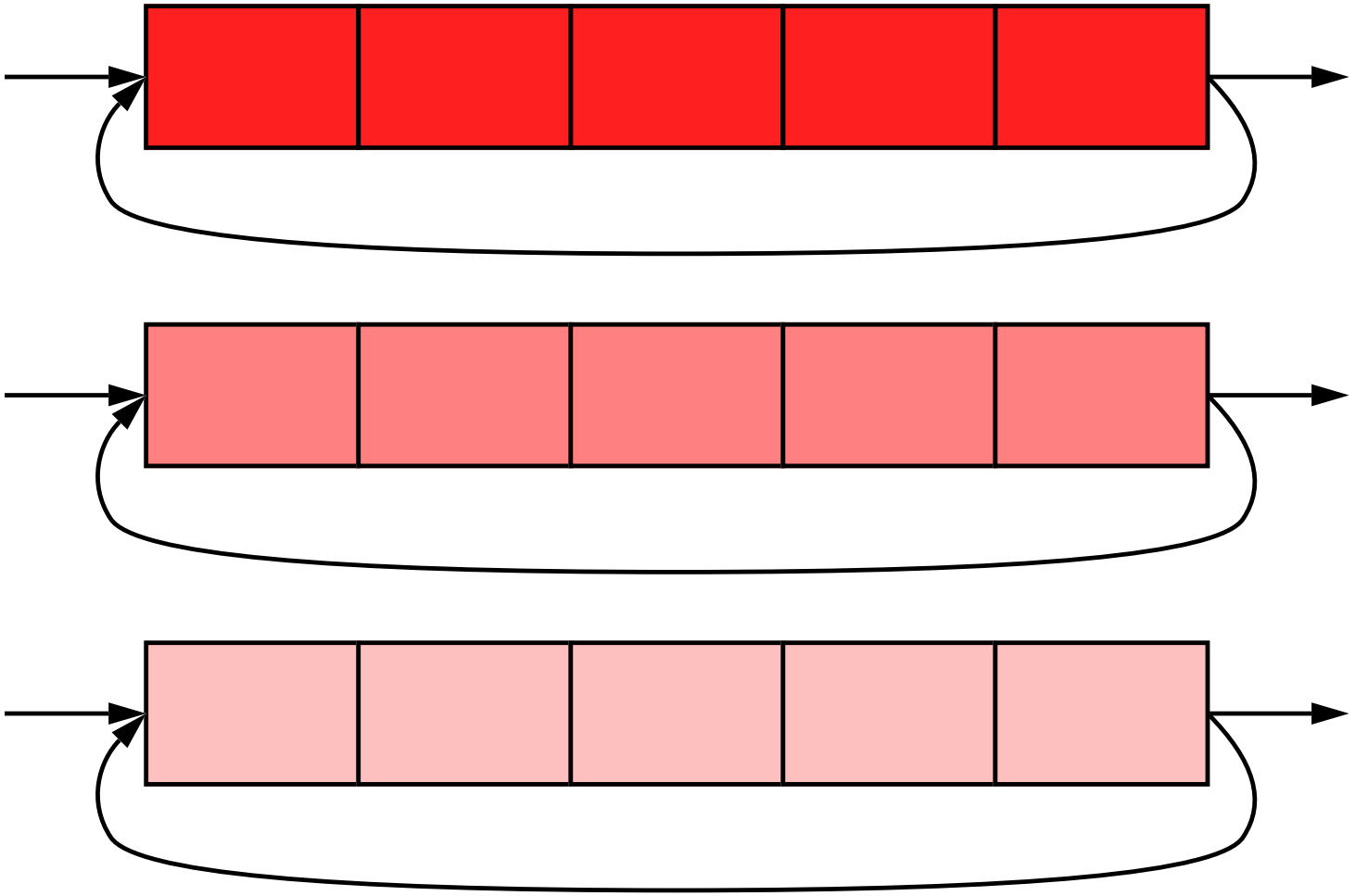
- This is basically *"processor sharing"*

Scheduling for Interactive Systems

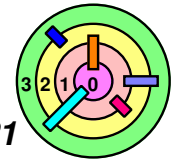
- *Length of "jobs" not known*
  - by the way, the round-robin scheduler works just fine without knowing the length of jobs
- Threads would give up the CPU voluntarily
  - they *block* for user input
- Would like to *favor interactive jobs*
  - use *priority queueing*



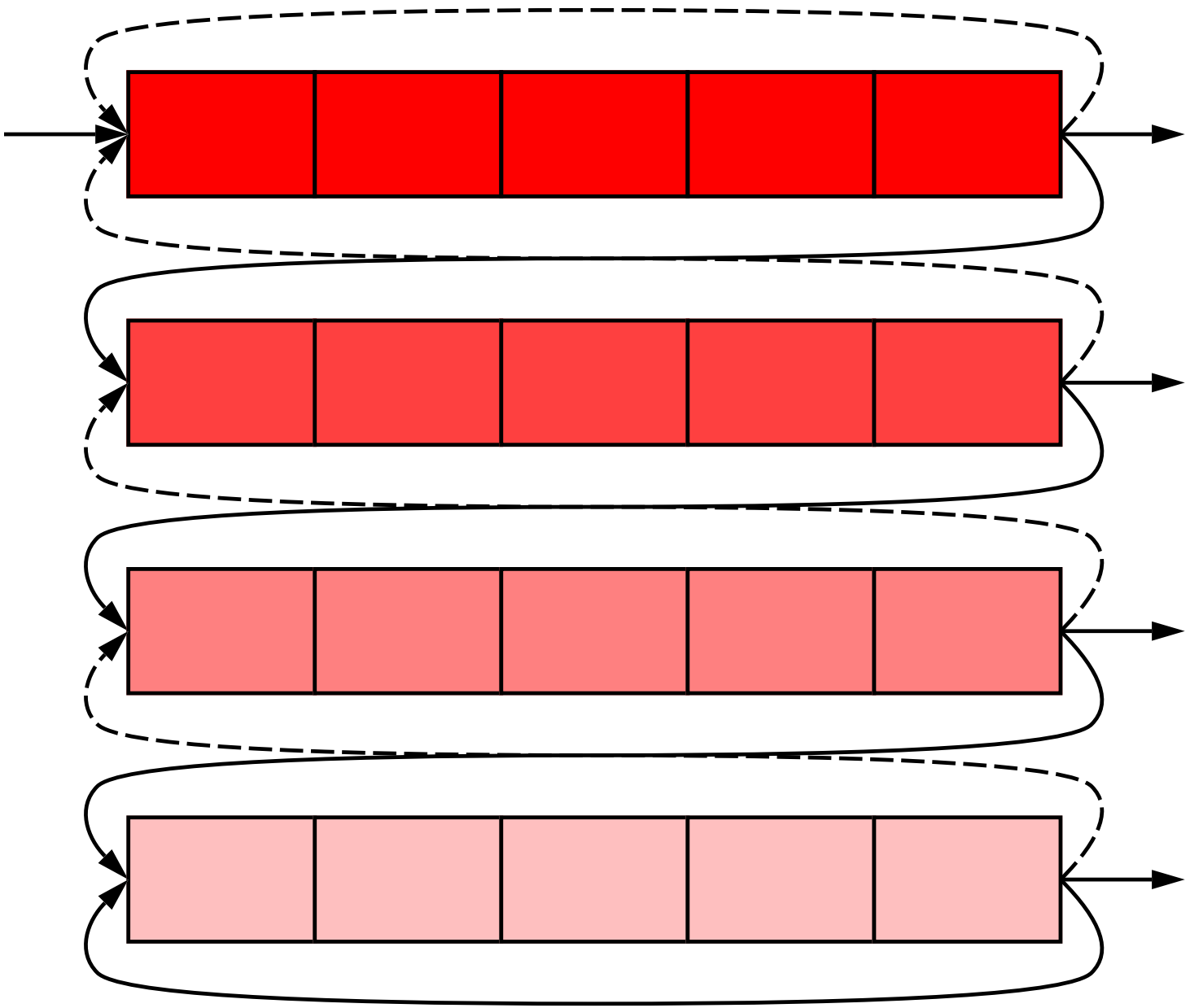
Round Robin with Priority

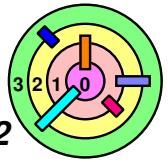


- *how* to determine priority?
  - let the threads themselves decide?



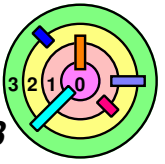
Multi-Level Feedback Queues





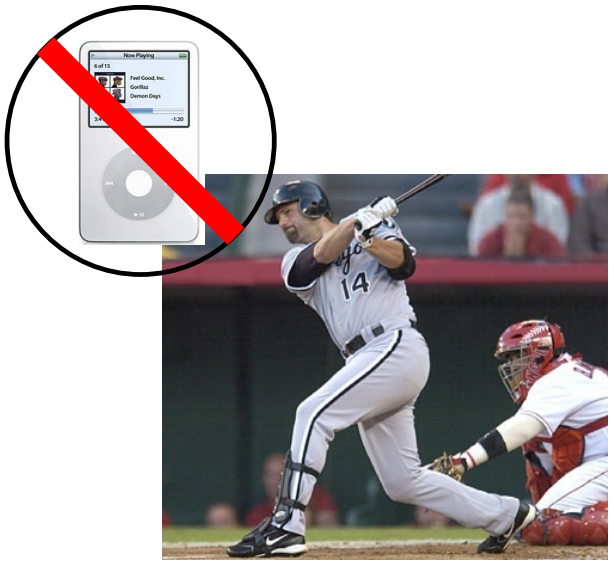
Multi-Level Feedback Queues

- When a thread got created, it gets highest priority
  - schedule it at the highest priority to observe what it does
    - if it *uses a full time slice*
      - *decrease its priority*
    - if it *blocks* before using up a full time slice
      - *increase its priority*
- To avoid starvation, use *aging*
  - if a job hasn't been run for a long time, increase its priority
- Clearly, not a fair scheduling algorithm

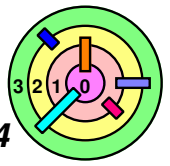


Real-Life Example

- Your iPod is broken
  - run mp3 player on your PC
- The baseball playoffs are on
  - streaming video
- An OS assignment is due
  - editor, compiler, debugger
- You've got to do everything on one computer
- Can your scheduler hack it?
- What scheduler is suitable for a general purpose system?

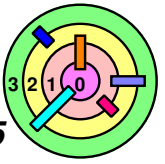


```
static int msync_interval(struct vm_area_struct * vma,
   unsigned long start, unsigned long end, int flags)

   int ret = 0;
   struct file * file = vma->vm_file;

   if ((flags & MS_INVALIDATE) && (vma->vm_flags & VM_LOCKED))
      return -EBUSY;

   if (file && (vma->vm_flags & VM_SHARED)) {
      ret = filemap_sync(vma, start, end-start, flags);

      if (!ret && (flags & MS_SYNC)) {
         struct address_space *mapping = file->f_mapping;
         int err;
```



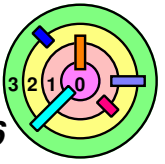
Interactive Scheduling

- *Time-sliced*, *priority-based*, *preemptive*
  - e.g., multi-level feedback queues
- Priority depends on expected time to block
  - interactive threads should have high priority
  - compute threads should have low priority
- Other heuristics
  - e.g., determine priority using *long term history* (not just immediate history)
    - processor usage causes decrease
    - sleeping causes increase



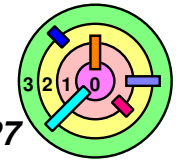
Scheduling for Fairness

- If *fairness* is really important, what would you do?
- Ex: shared servers
  - you and four friends each contribute $1000 towards a server
    - you, rightfully, feel you own 20% of it
  - your friends are into threads, you're not
    - they run 5-threaded programs
    - you run a 1-threaded program
  - their programs each get 5/21 of the processor
  - your programs get 1/21 of the processor



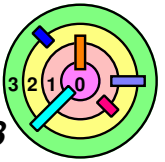
Lottery Scheduling

- 25 lottery tickets are distributed equally to you and your four friends
  - you give 5 tickets to your one thread
  - they give one ticket each to their threads
- A lottery is held for every scheduling decision
  - your thread is 5 times more likely to win than the others

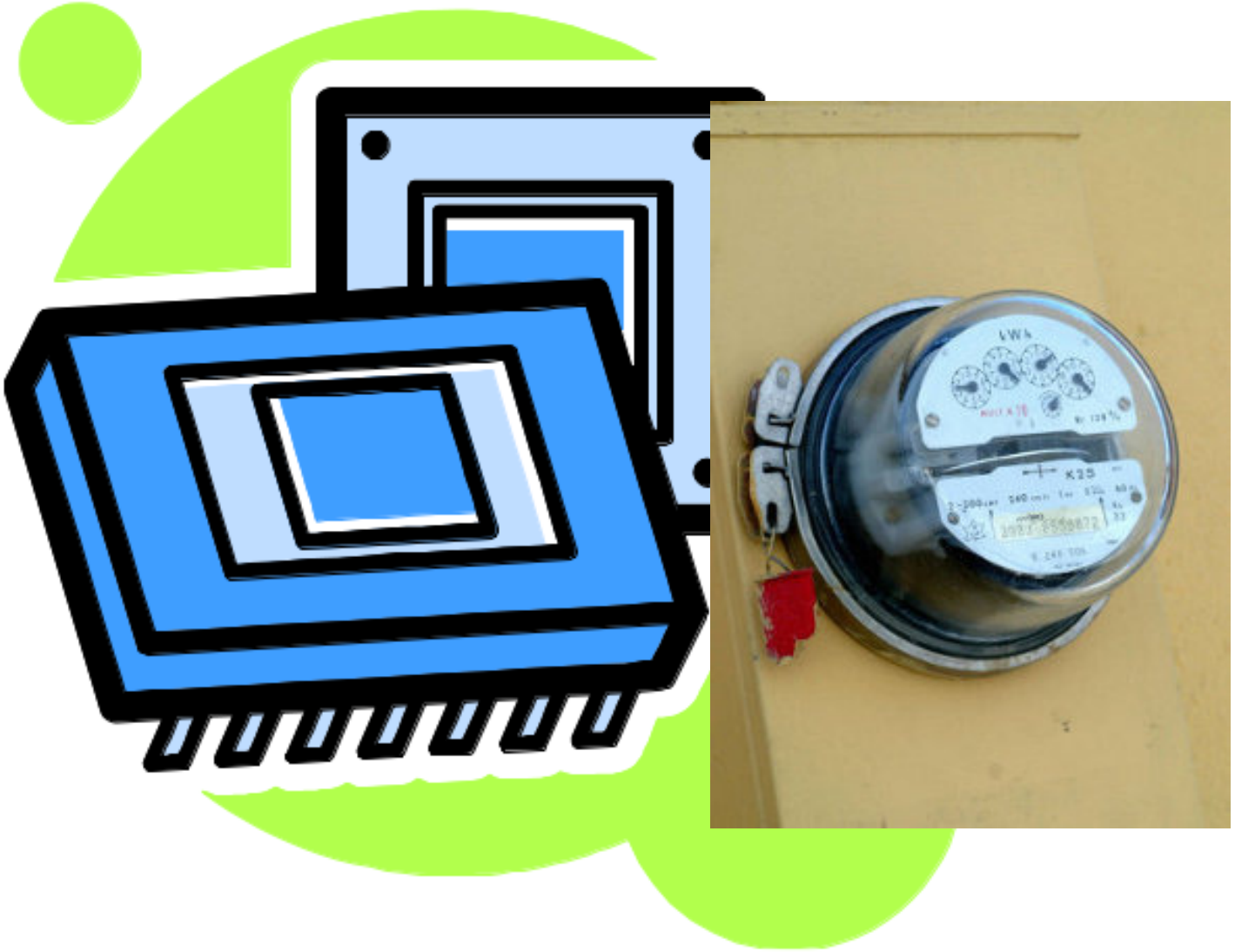


Proportional-Share Scheduling

- Stride scheduling
  - 1995 paper by Waldspurger and Weihl
- Completely fair scheduling (CFS)
  - added to Linux in 2007



Metered Processors

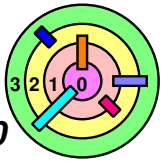


- the textbook presented *Stride Scheduling* differently
  - as far as exam goes, stick to our presentation

Stride Scheduling Algorithm

- *Time-sliced*, *priority-based*, *preemptive*
  - every thread is assigned a priority, called a *pass* value
    - single queue, *sorted based on pass values*, *smallest first*
  - every thread is assigned a *stride* value
    - stride values are computed according to *distribution of tickets* in a lottery scheduling scheme

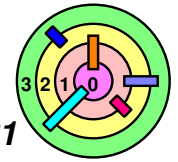
- In every iteration / time-slice
  1) shedule the thread with the *smallest pass value* (at the head of the queue)
  2) set the *global pass value* to be the pass value of this thread
  3) *increment* the thread's *pass* value by its *stride* value
  4) loop



Stride Scheduling Example

- Stride $\propto$ 1 / number of tickets

Thread	Tickets	Stride
A	3	
B	2	
C	1	

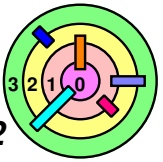


Stride Scheduling Example

- Stride $\propto$ 1 / number of tickets

Thread	Tickets	Stride
A	3	1/3
B	2	1/2
C	1	1

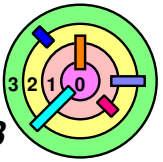
then multiply by smallest common multiplier of denominators to get *interger stride widths* (here and for *exams*)



Stride Scheduling Example

- Stride $\propto$ 1 / number of tickets

Thread	Tickets	Stride
A	3	2
B	2	3
C	1	6



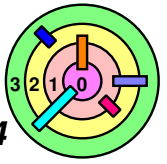
Stride Scheduling Example

- Stride $\propto$ 1 / number of tickets
  - every thread is initialized with a ***pass*** value

Thread	Tickets	Stride
A	3	2
B	2	3
C	1	6

can start with any pass values (e.g., determined by the ***current state*** of the stride scheduler)

itr	A	B	C
1	1	2	3



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Thread	Tickets	Stride
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C	1	6

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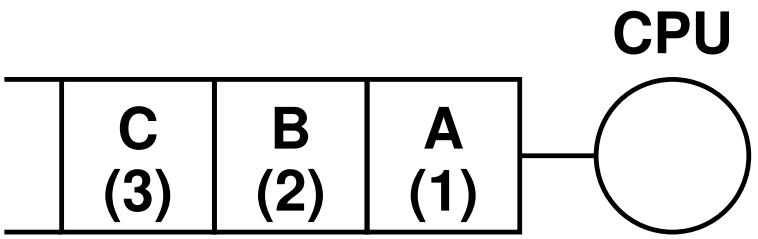

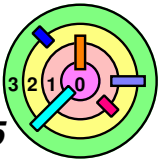

Stride Scheduling Example

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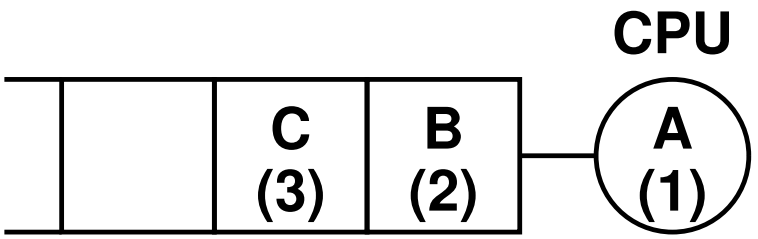
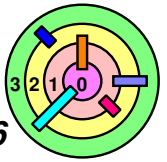
Thread	Tickets	Stride
A	3	2
B	2	3
C	1	6

itr	A	B	C
1	(1)	2	3



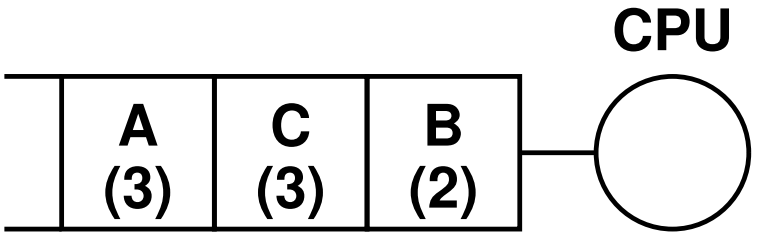


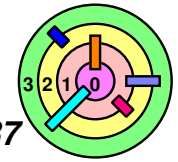
Stride Scheduling Example

- Stride $\propto$ 1 / number of tickets
  - every thread is initialized with a ***pass*** value

Thread	Tickets	Stride
A	3	2
B	2	3
C	1	6

itr	A	B	C
1	(1)	2	3
2	3	2	3





Stride Scheduling Example

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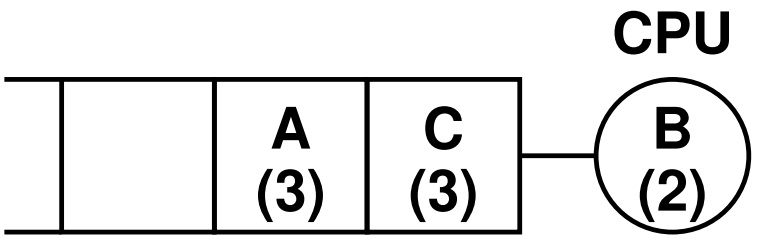
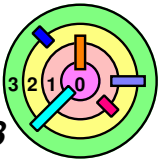


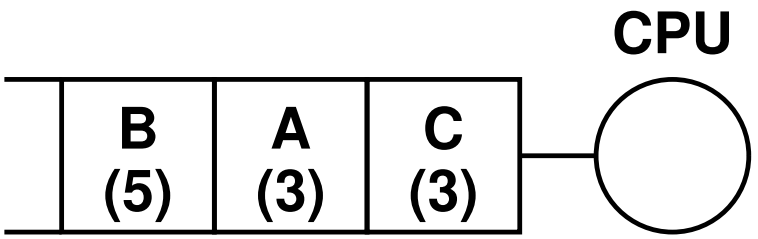


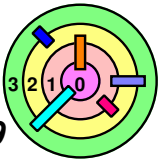
Stride Scheduling Example

- Stride $\propto$ 1 / number of tickets
  - every thread is initialized with a ***pass*** value

Thread	Tickets	Stride
A	3	2
B	2	3
C	1	6

itr	A	B	C
1	(1)	2	3
2	3	(2)	3
3	3	5	3





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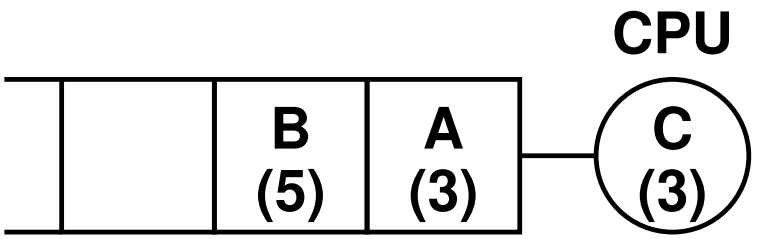
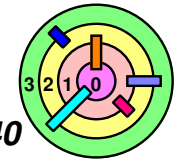
3	3	5	(3)



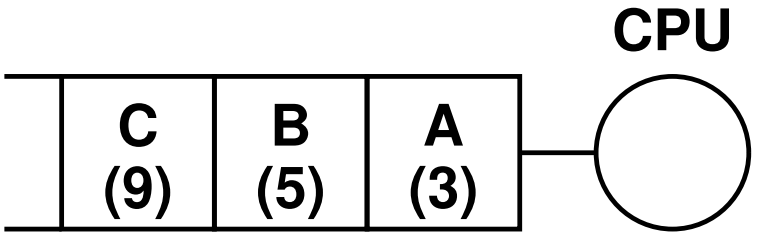


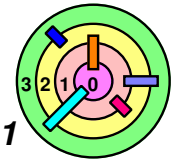
Stride Scheduling Example

- Stride $\propto$ 1 / number of tickets
  - every thread is initialized with a ***pass*** value

Thread	Tickets	Stride
A	3	2
B	2	3
C	1	6

itr	A	B	C
1	(1)	2	3
2	3	(2)	3
3	3	5	(3)
4	3	5	9





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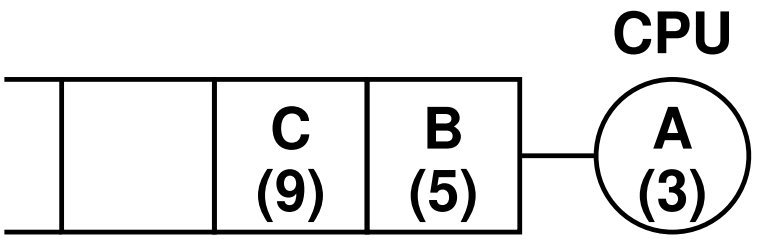

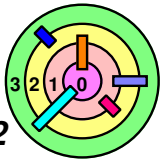

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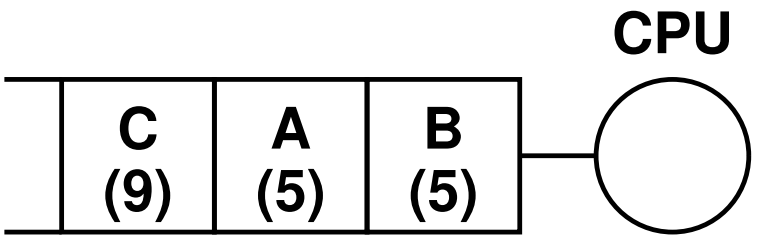

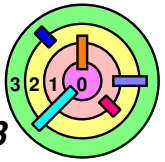

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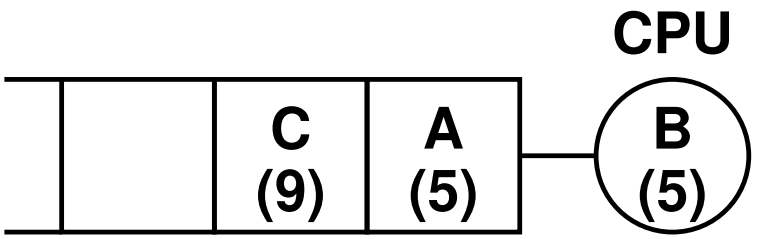

itr	A	B	C
1	(1)	2	3
2	3	(2)	3
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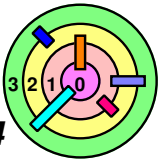
4	(3)	5	9
5	5	(5)	9



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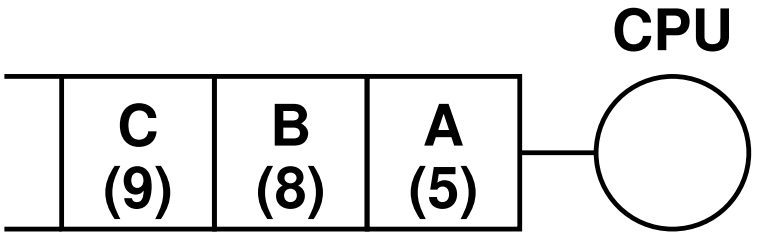
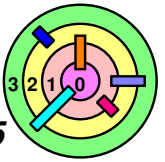


itr	A	B	C
1	(1)	2	3
2	3	(2)	3
3	3	5	(3)
4	(3)	5	9
5	5	(5)	9
6	5	8	9



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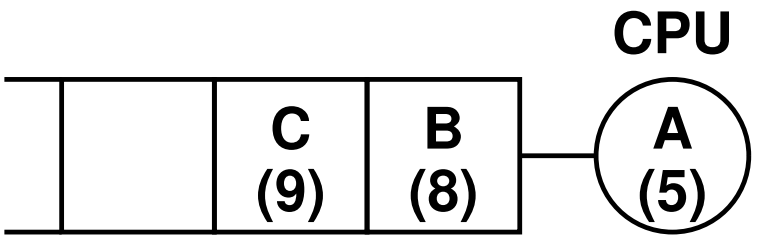

itr	A	B	C
1	(1)	2	3
2	3	(2)	3
3	3	5	(3)
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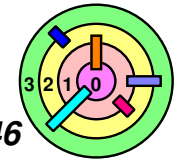
5	5	(5)	9
6	(5)	8	9



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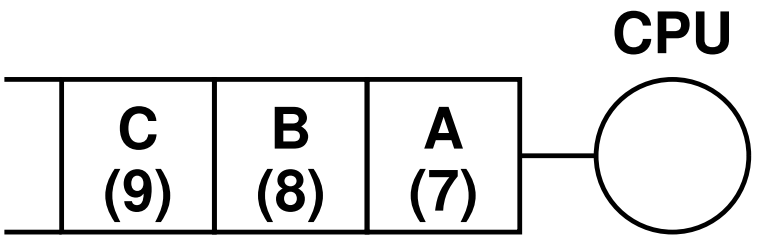
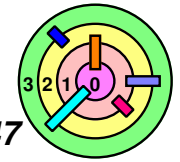


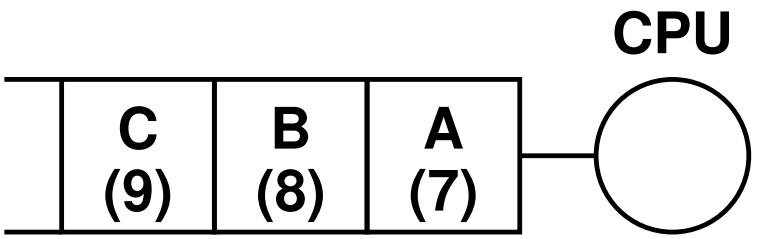
itr	A	B	C
1	(1)	2	3
2	3	(2)	3
3	3	5	(3)
4	(3)	5	9
5	5	(5)	9
6	(5)	8	9
7	7	8	9



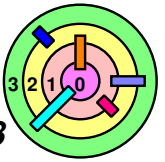
Stride Scheduling Example

- Stride ∝ 1 / number of tickets
  - every thread is initialized with a ***pass*** value
- Conforms to the distribution of tickets!

Thread	Tickets	Stride
A	3	2
B	2	3
C	1	6

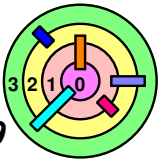


itr	A	B	C
1	(1)	2	3
2	3	(2)	3
3	3	5	(3)
4	(3)	5	9
5	5	(5)	9
6	(5)	8	9
7	7	8	9



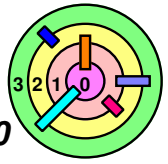
Stride Scheduling - Additional Details

- New thread
  - allocate the *global pass value*
    - so it gets to run first
- Thread uses less than its quantum
  - let 0 < f < 1
  - pass += f × stride
  - the result is that *interactive threads* get *higher priority*



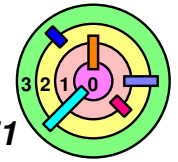
Scheduling in Hard Real Time Systems

- Known chores and durations
  - find schedule satisfying constraints
  - uniprocessor
    - rate-monotonic scheduling of *cyclic chores*, i.e., *periodic tasks*
      - $t_i \rightarrow T_i, P_i$ where T is *execution time* and P is *period*
      - e.g., a job is required to execute 2 seconds every 6 seconds
      - deadline is implied
    - Earliest Deadline First (EDF)
      - $t_i \rightarrow d_i$ where d is a *deadline*
      - optimality proof exists under certain conditions
  - multiprocessor
    - often NP-complete ...



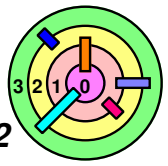
Assumptions

- Interrupts don't interfere (too much) with schedule
  - bounded interrupt delays
- Execution time really is predictable
  - what about effects of caching and paging?

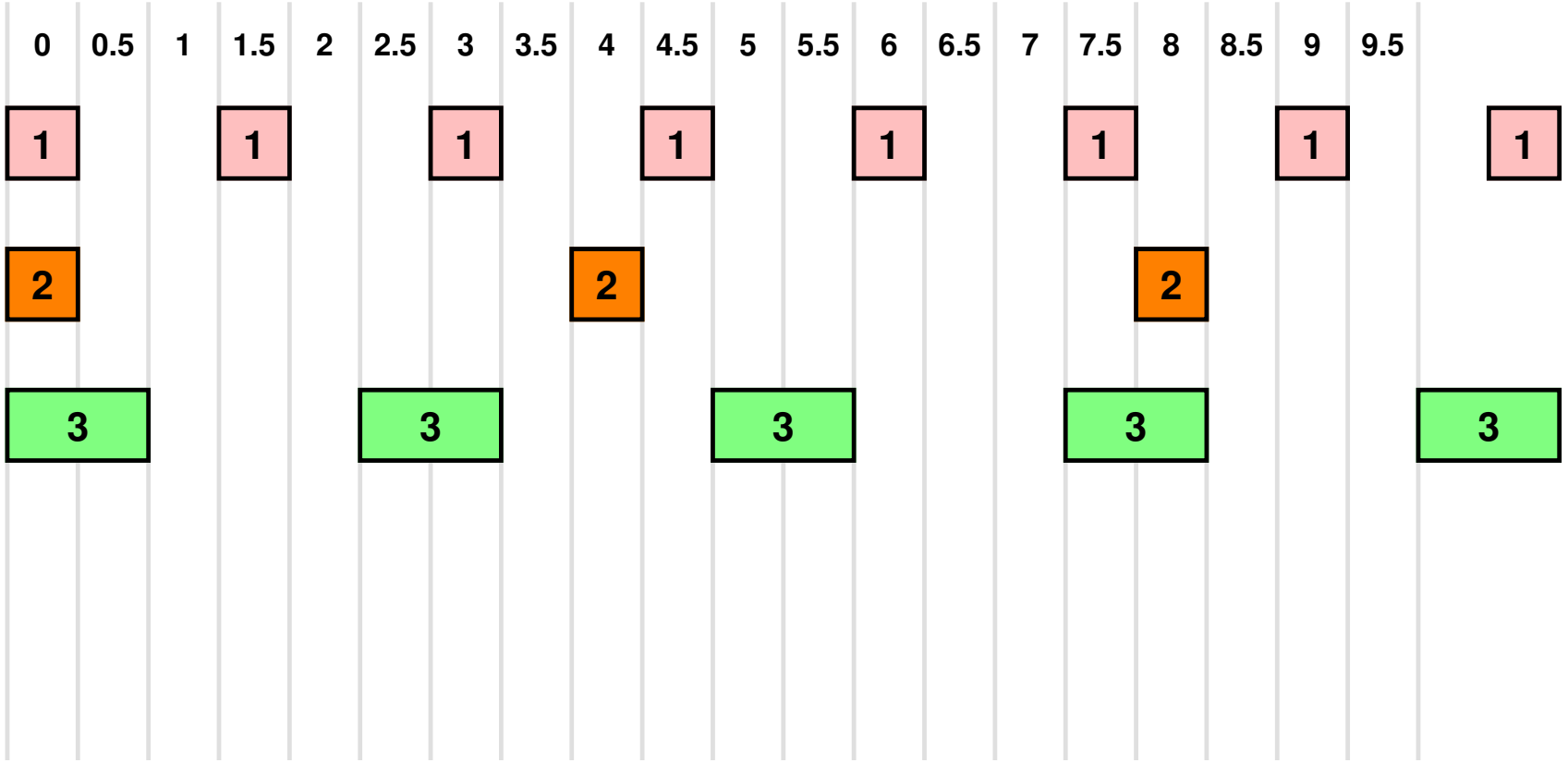


Rate-Monotonic Scheduling

- Periodic chores
  - period P_i
  - per-cycle processing time $T_i \ (\leq P_i)$
  - feasible if $\sum_{i=0}^{n-1} (T_i / P_i) \leq 1$
- Rate-monotonic scheduling
  - each chore *i* is handled by a thread with *priority* $1/P_i$
  - *preemptive*, *priority scheduling*
  - works when $\sum_{i=0}^{n-1} (T_i / P_i) \leq n(2^{1/n}-1)$
  - $= ln\ 2$ in the limit



Scenario 1



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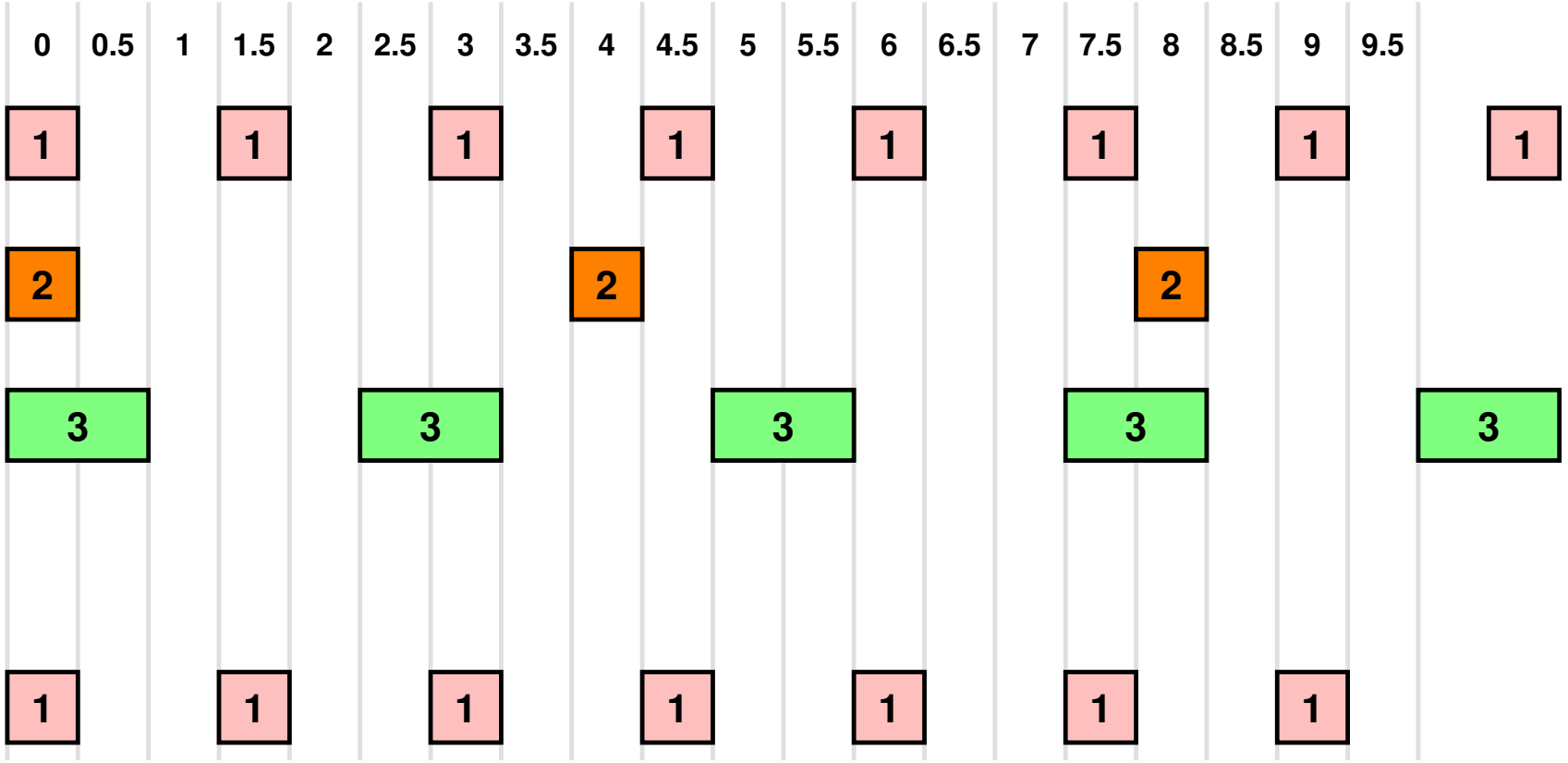

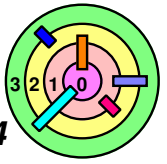

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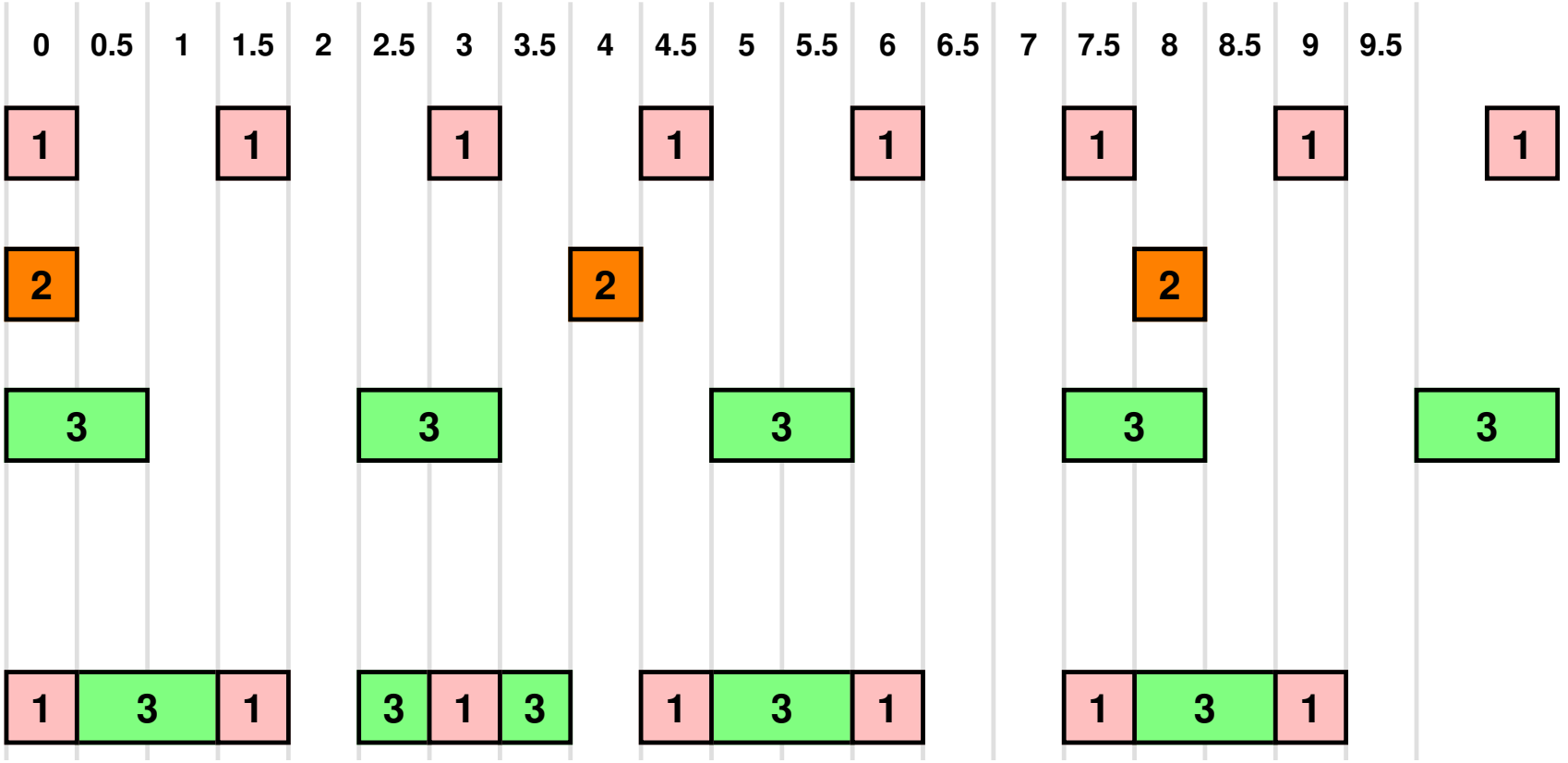

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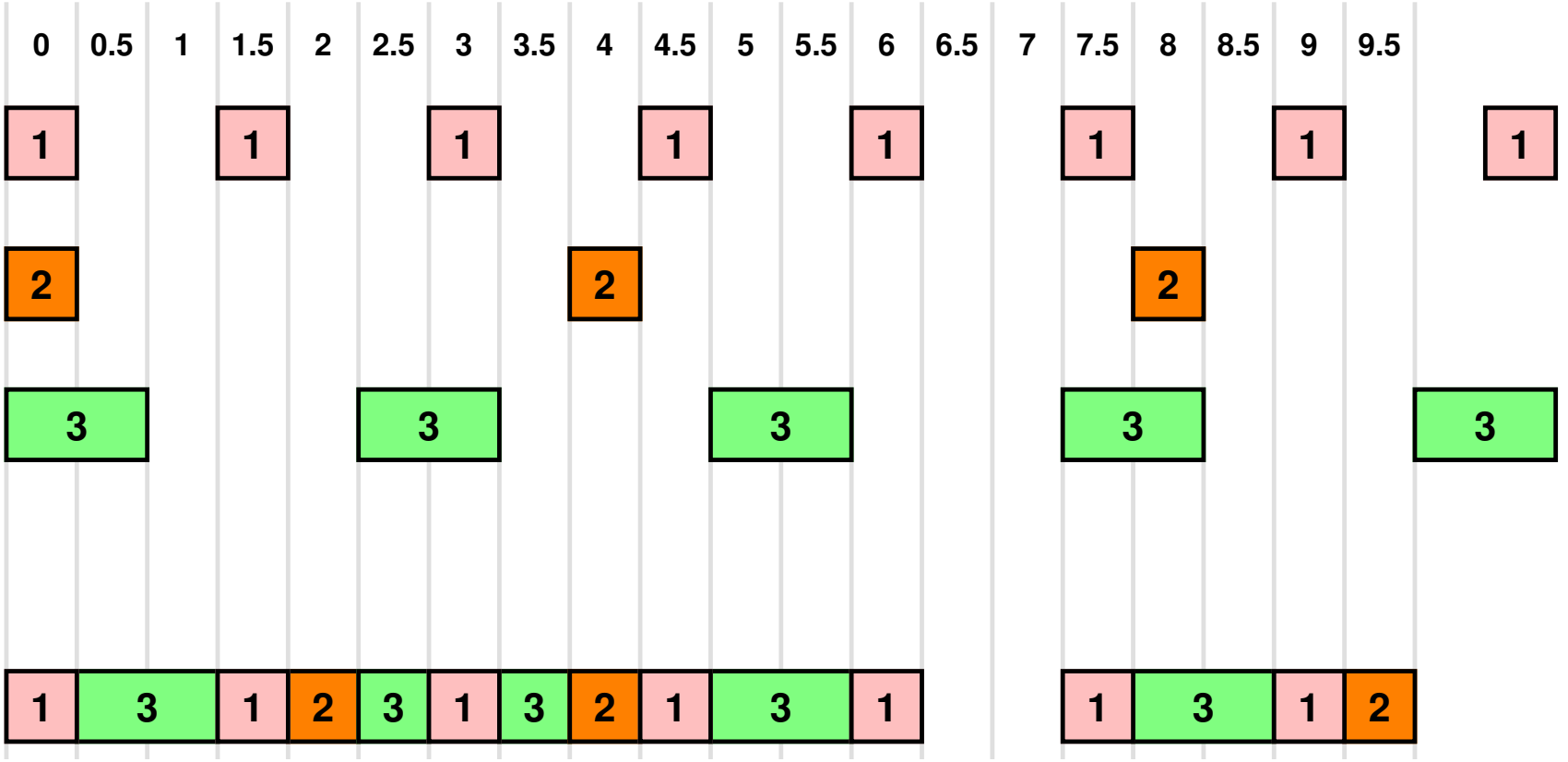
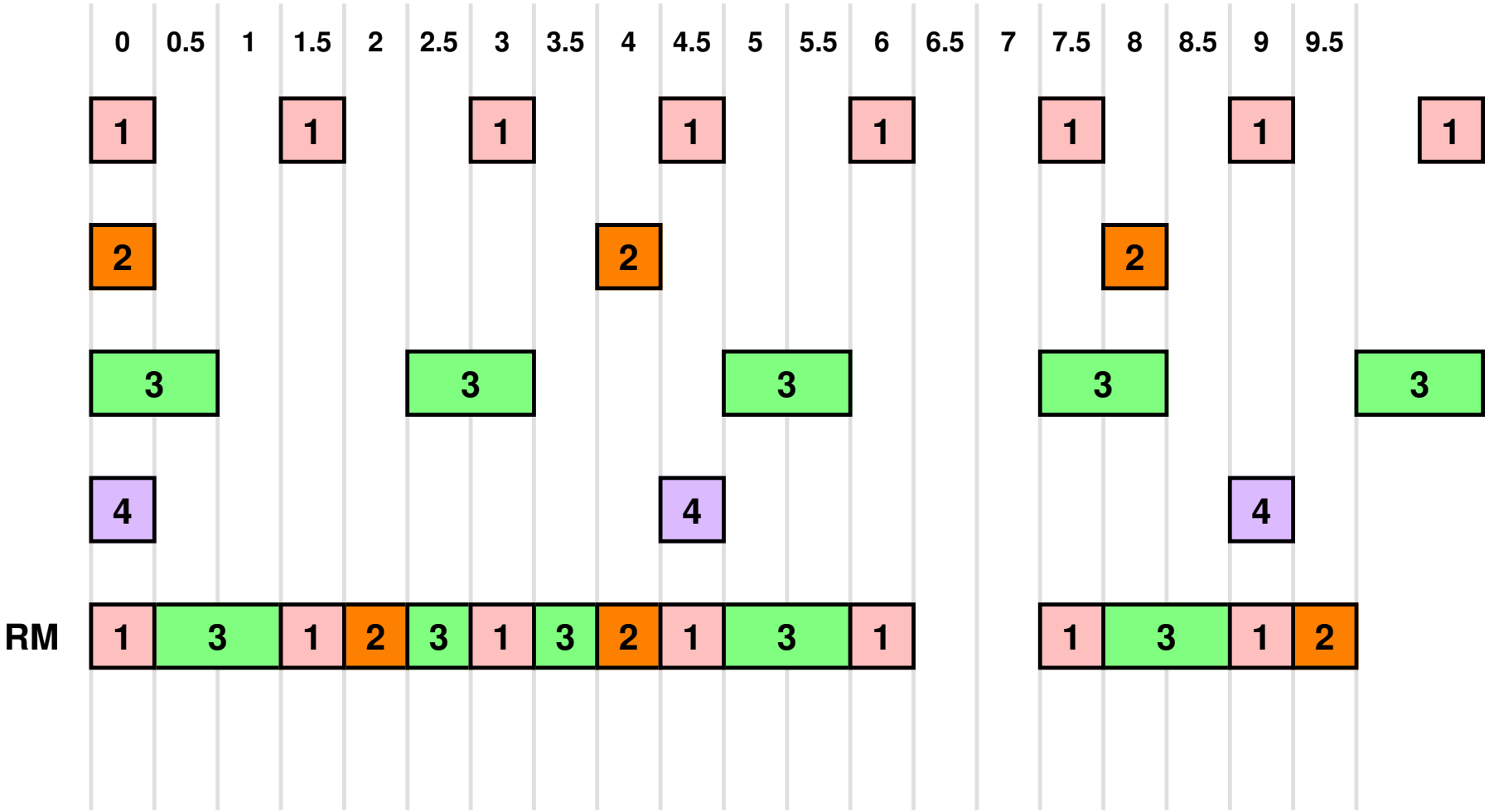
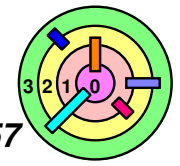


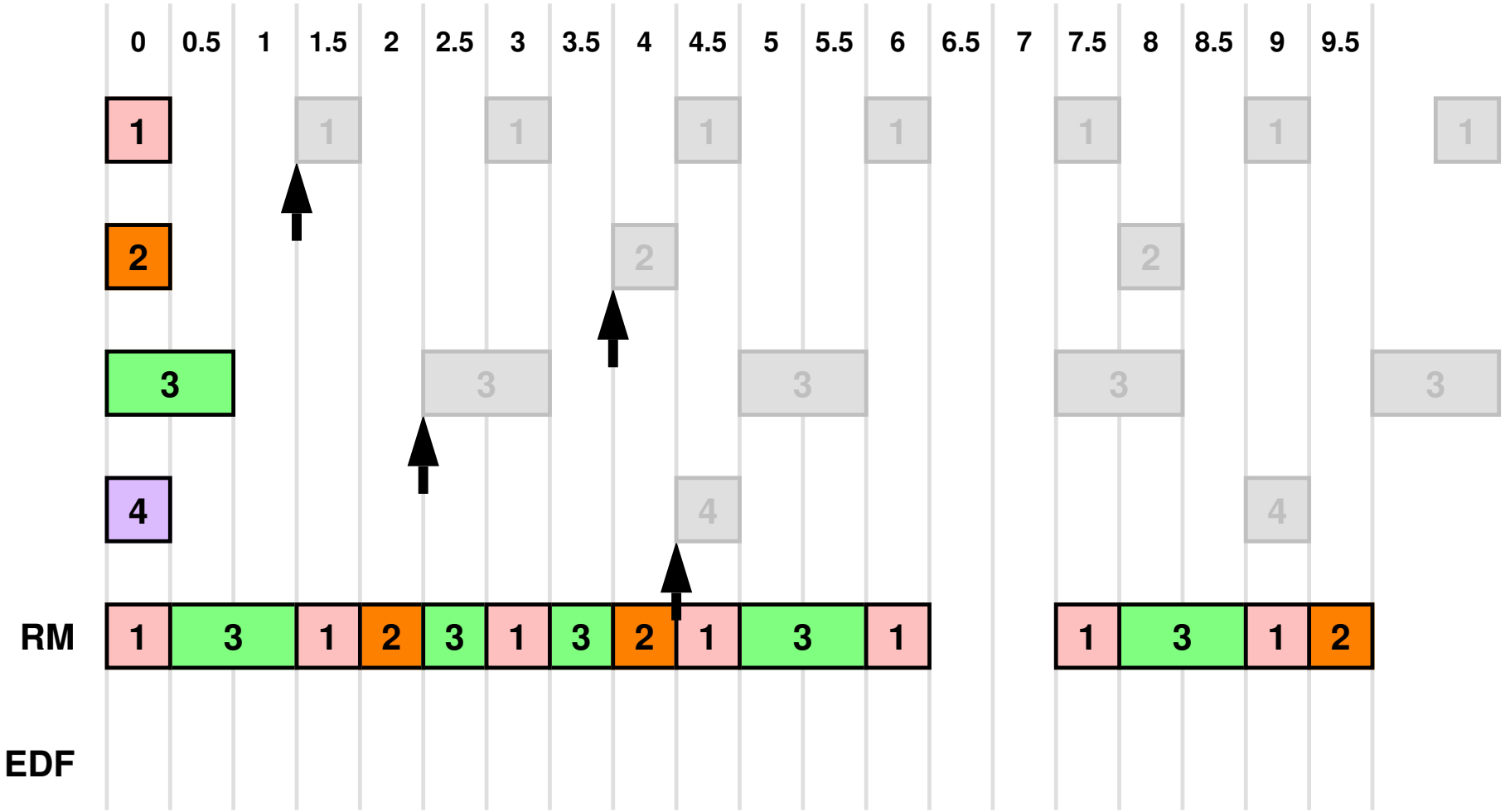
Scenario 2



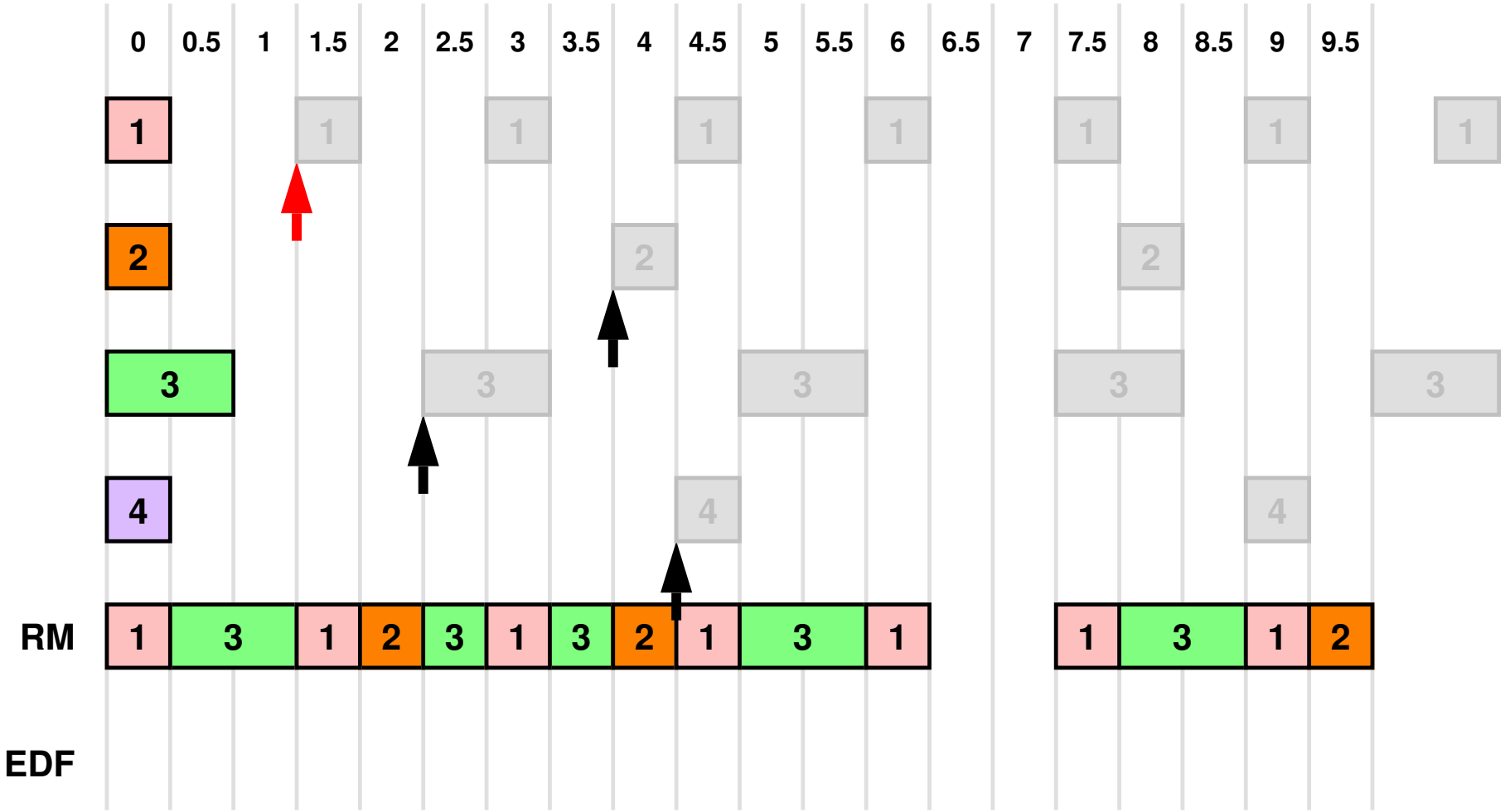
- rate-monotonic scheduler failed
- but EDF succeeds in this example



Earliest Deadline First



Earliest Deadline First



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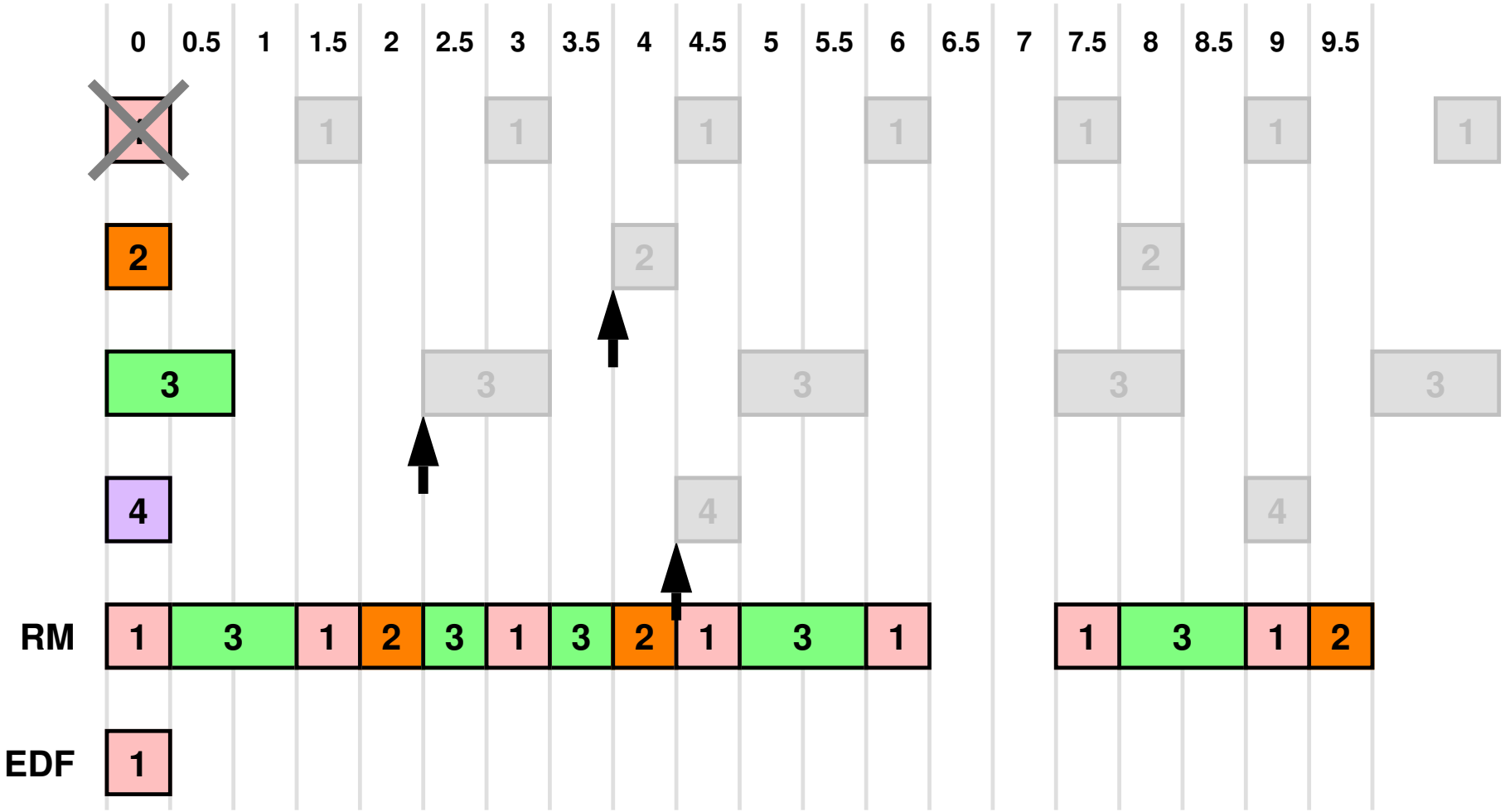

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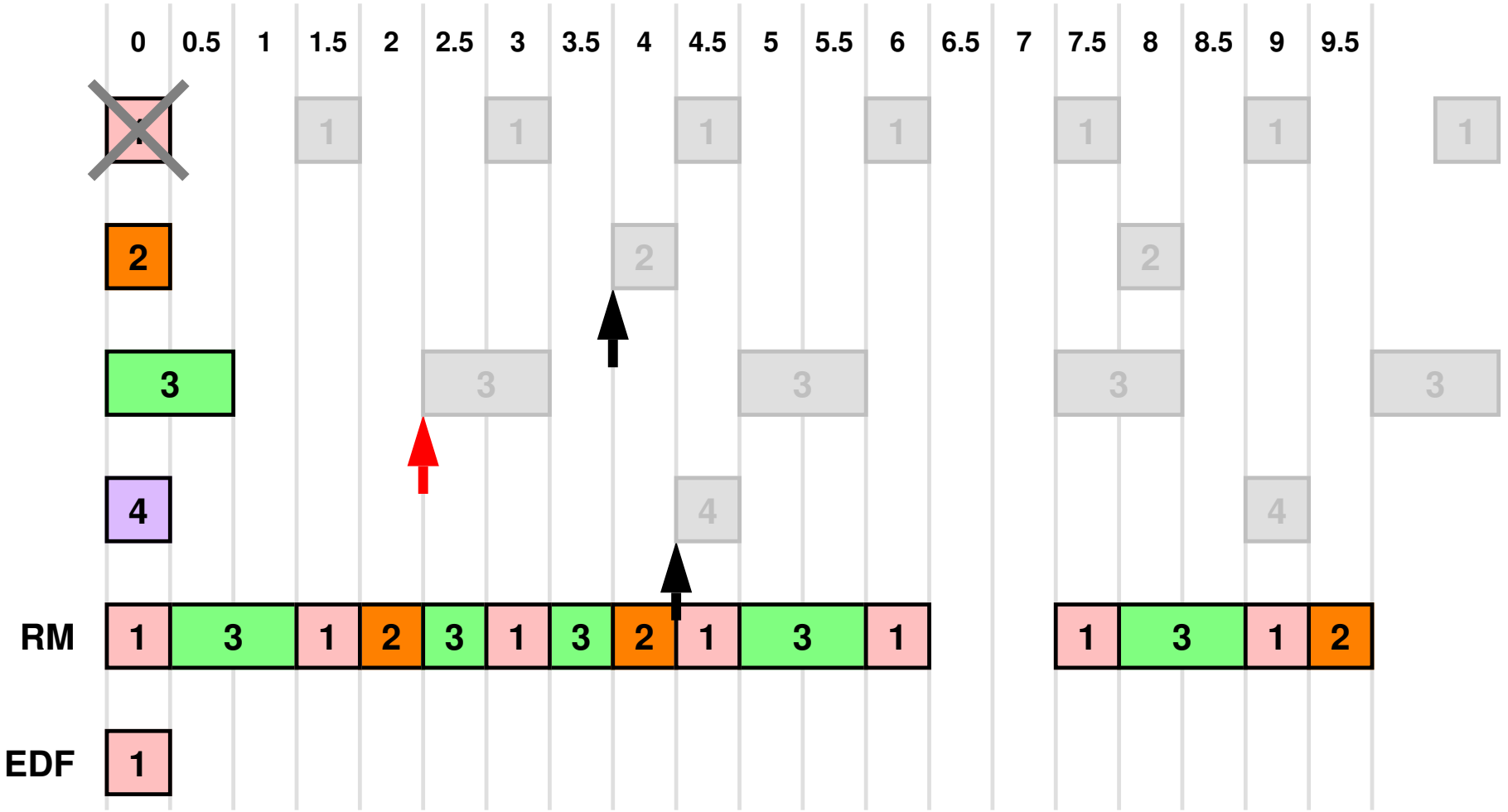

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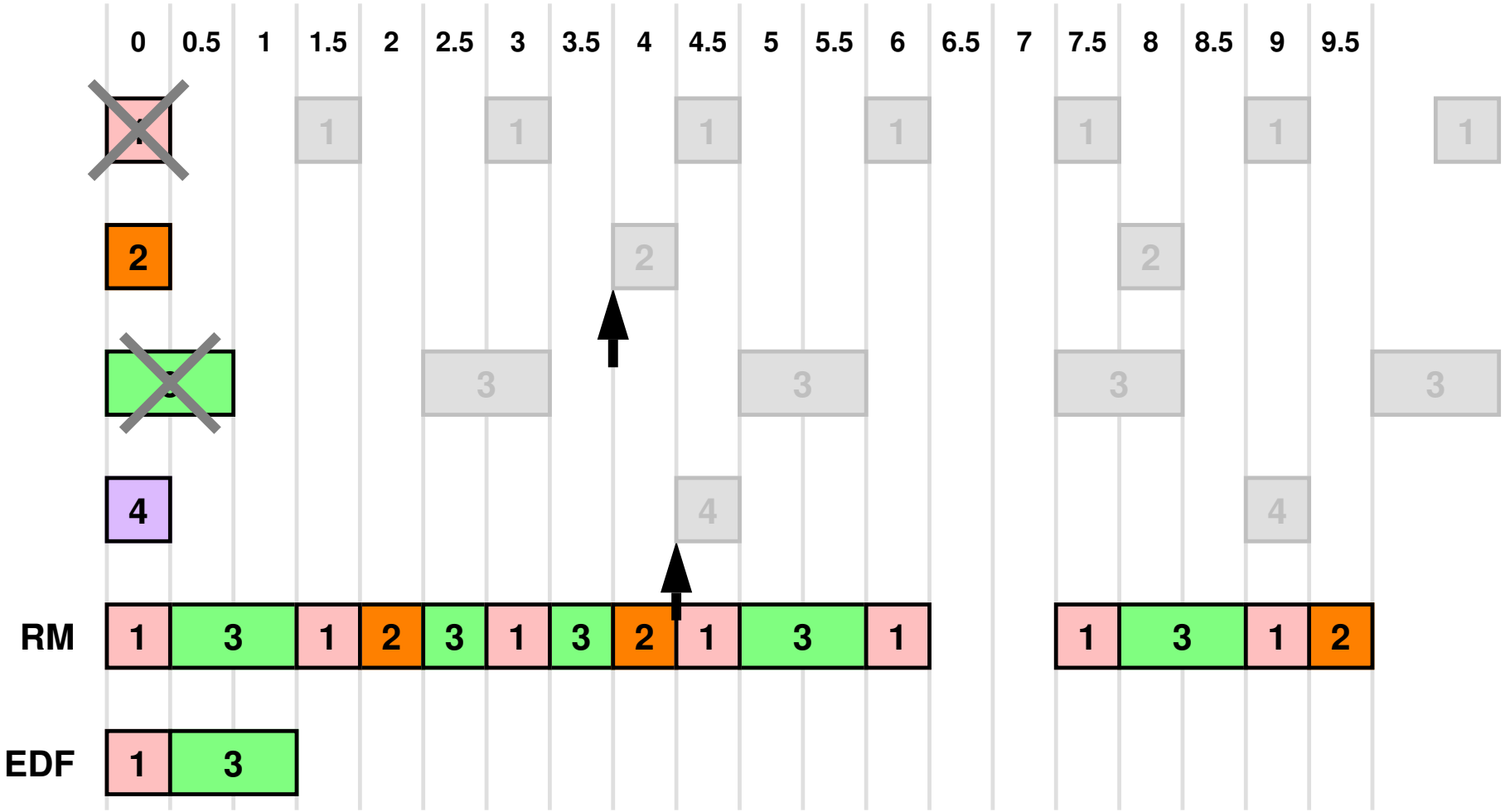

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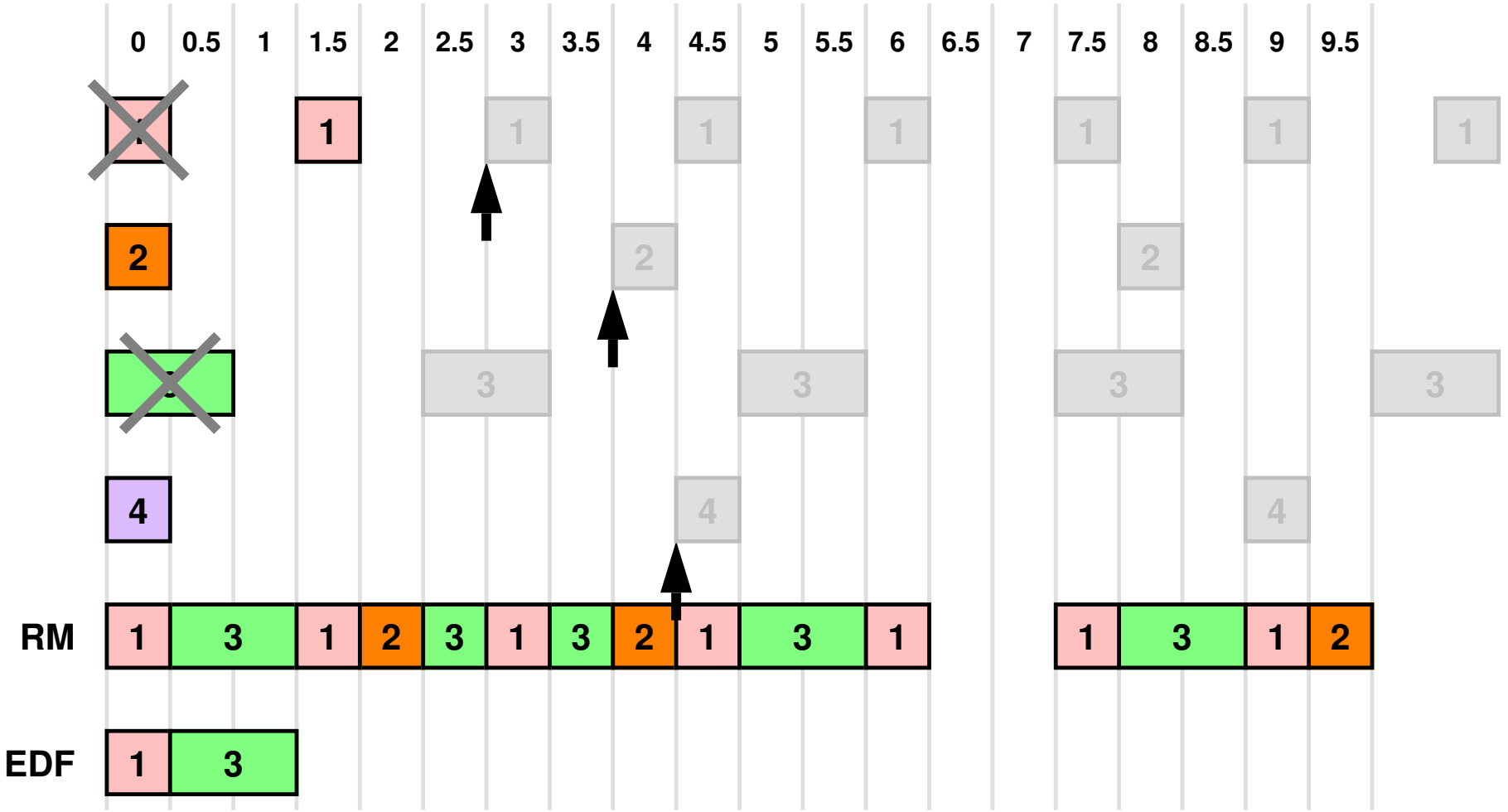

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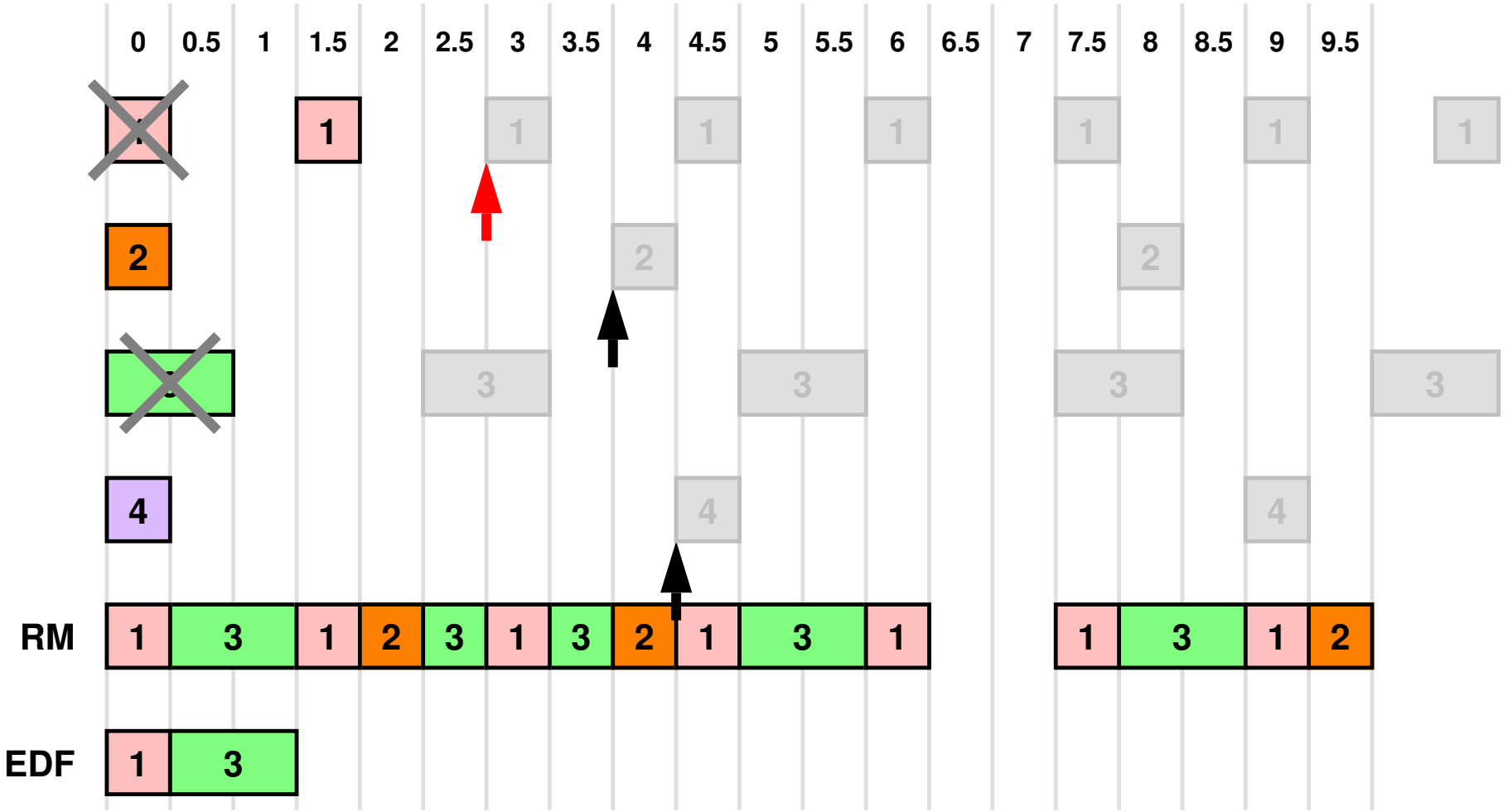

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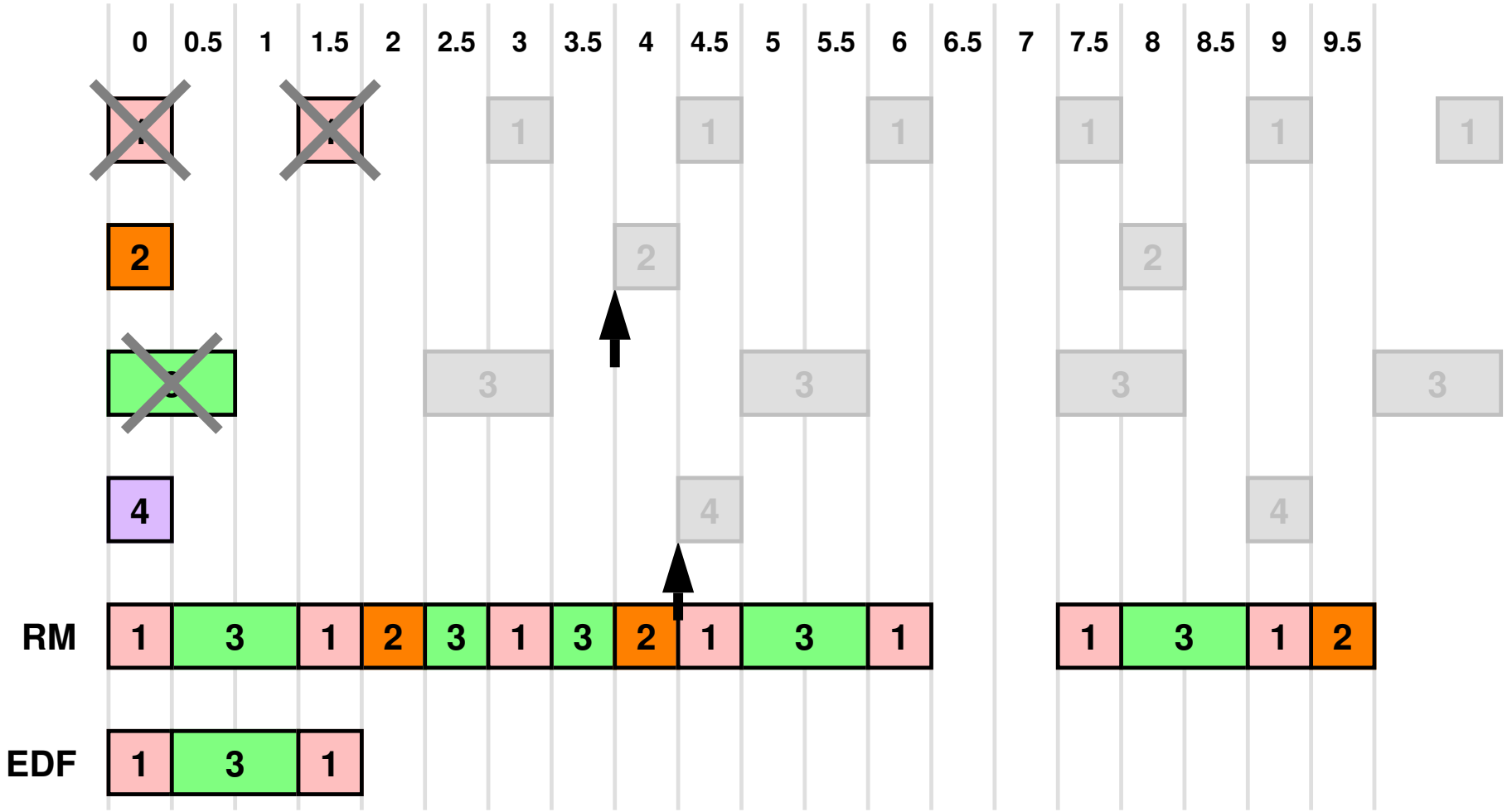

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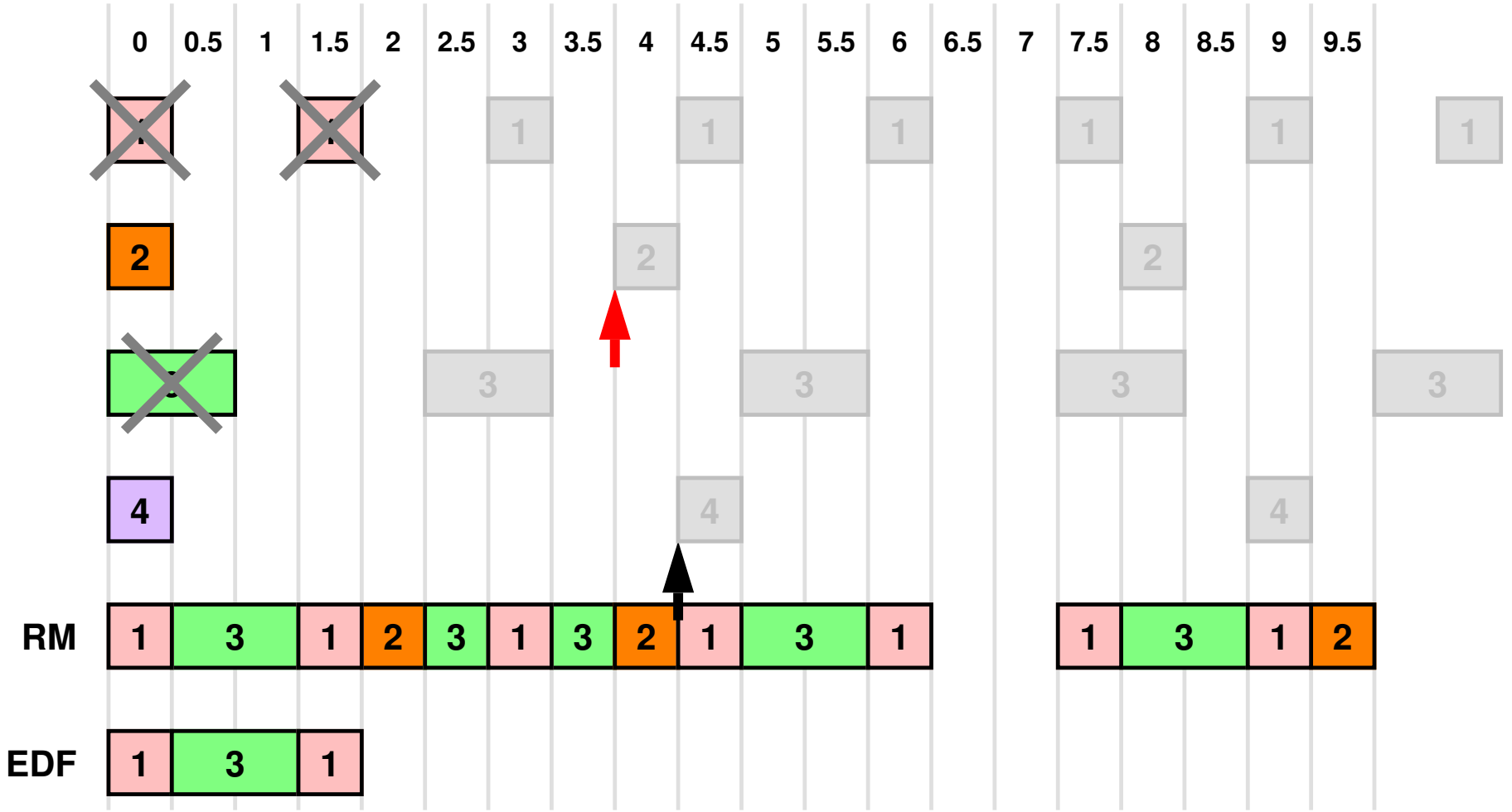

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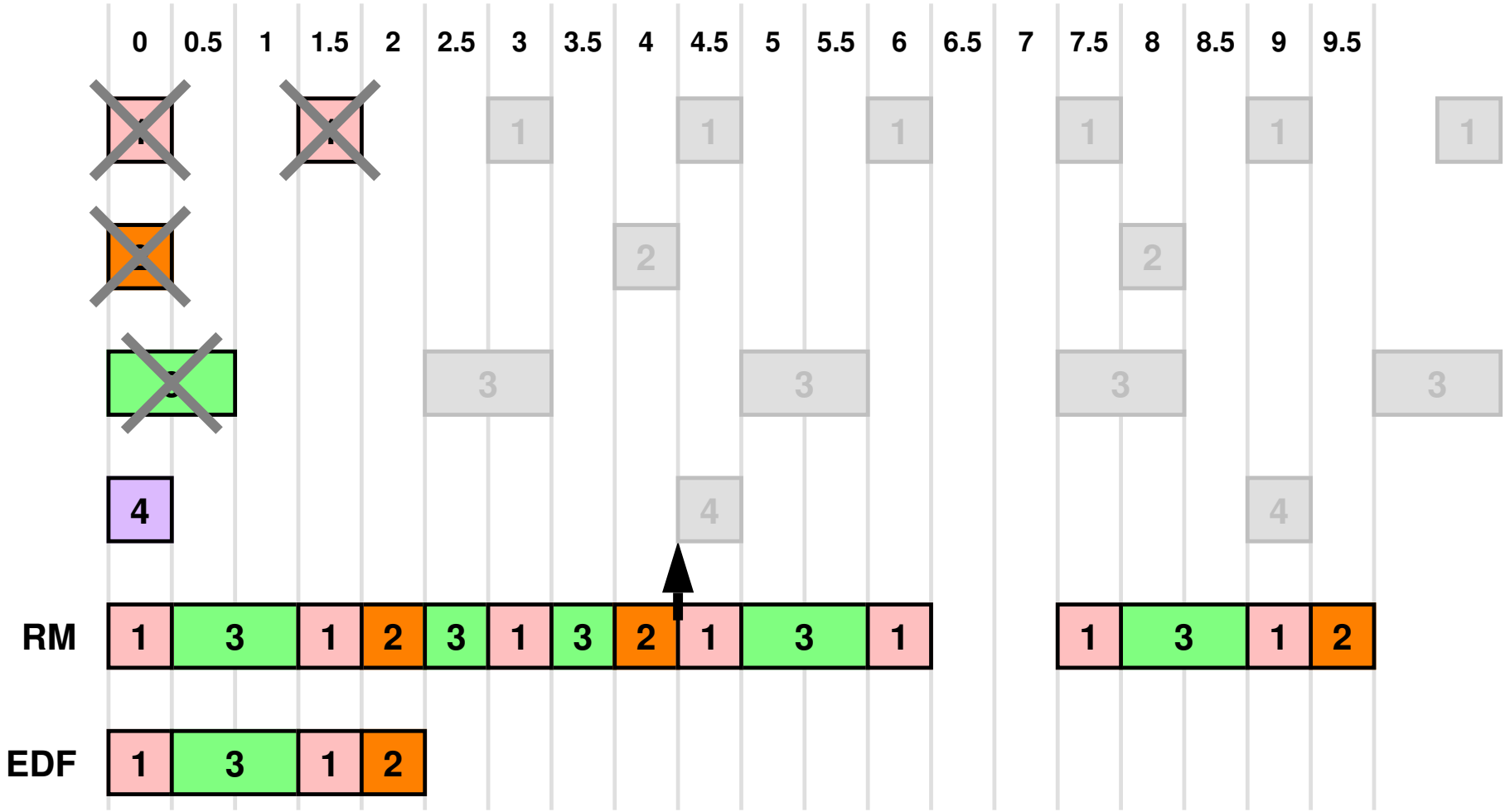

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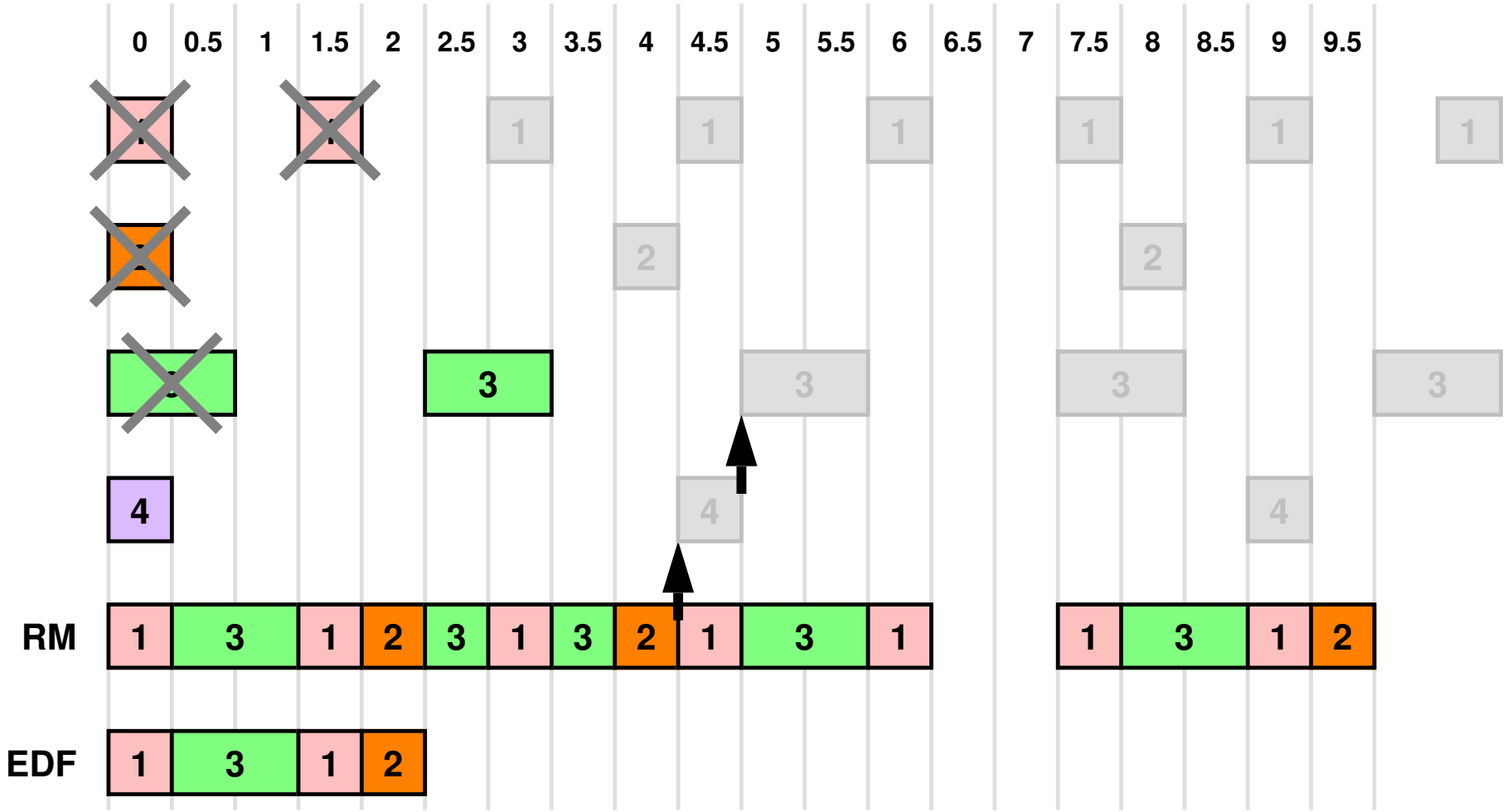

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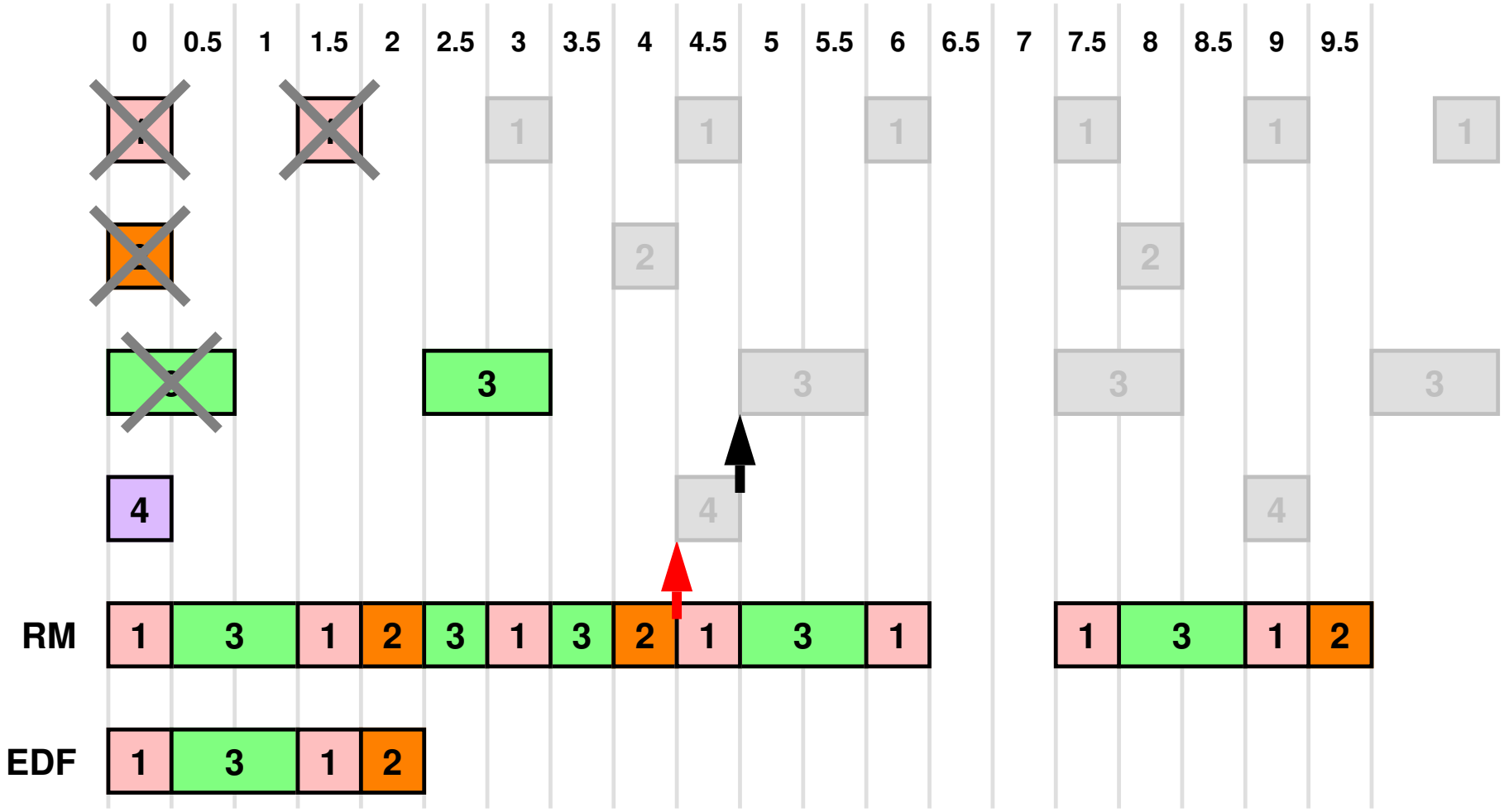

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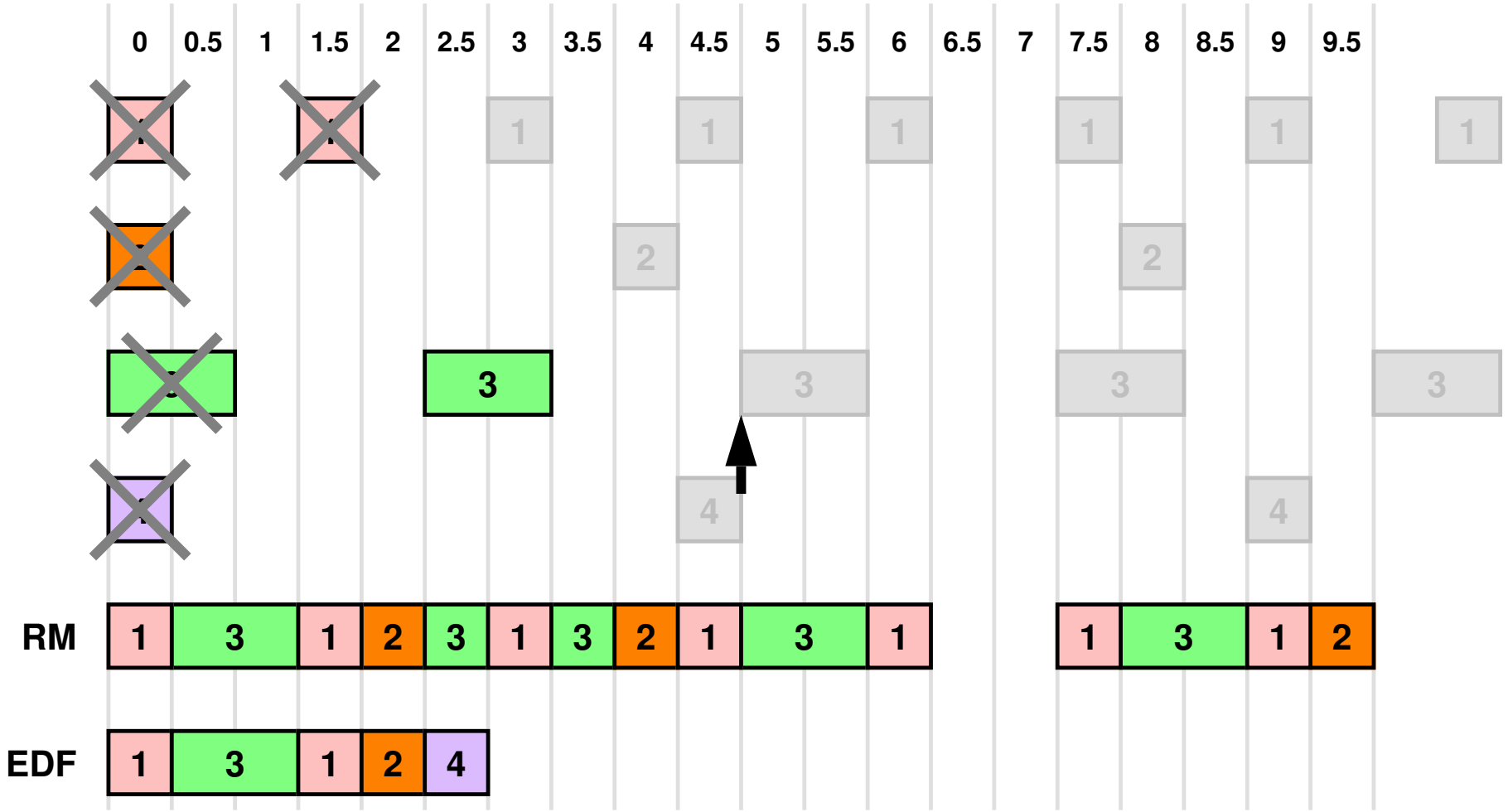

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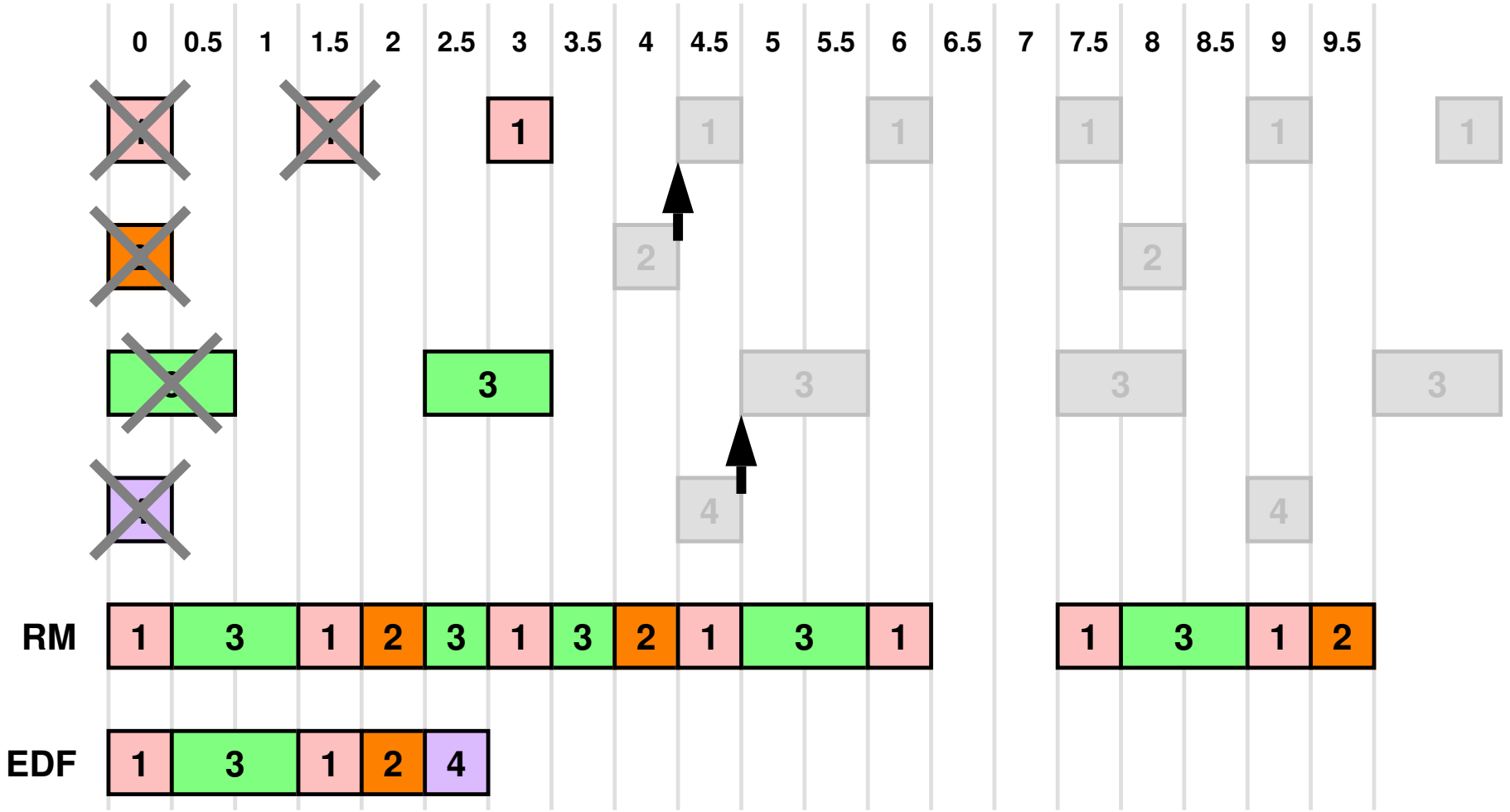

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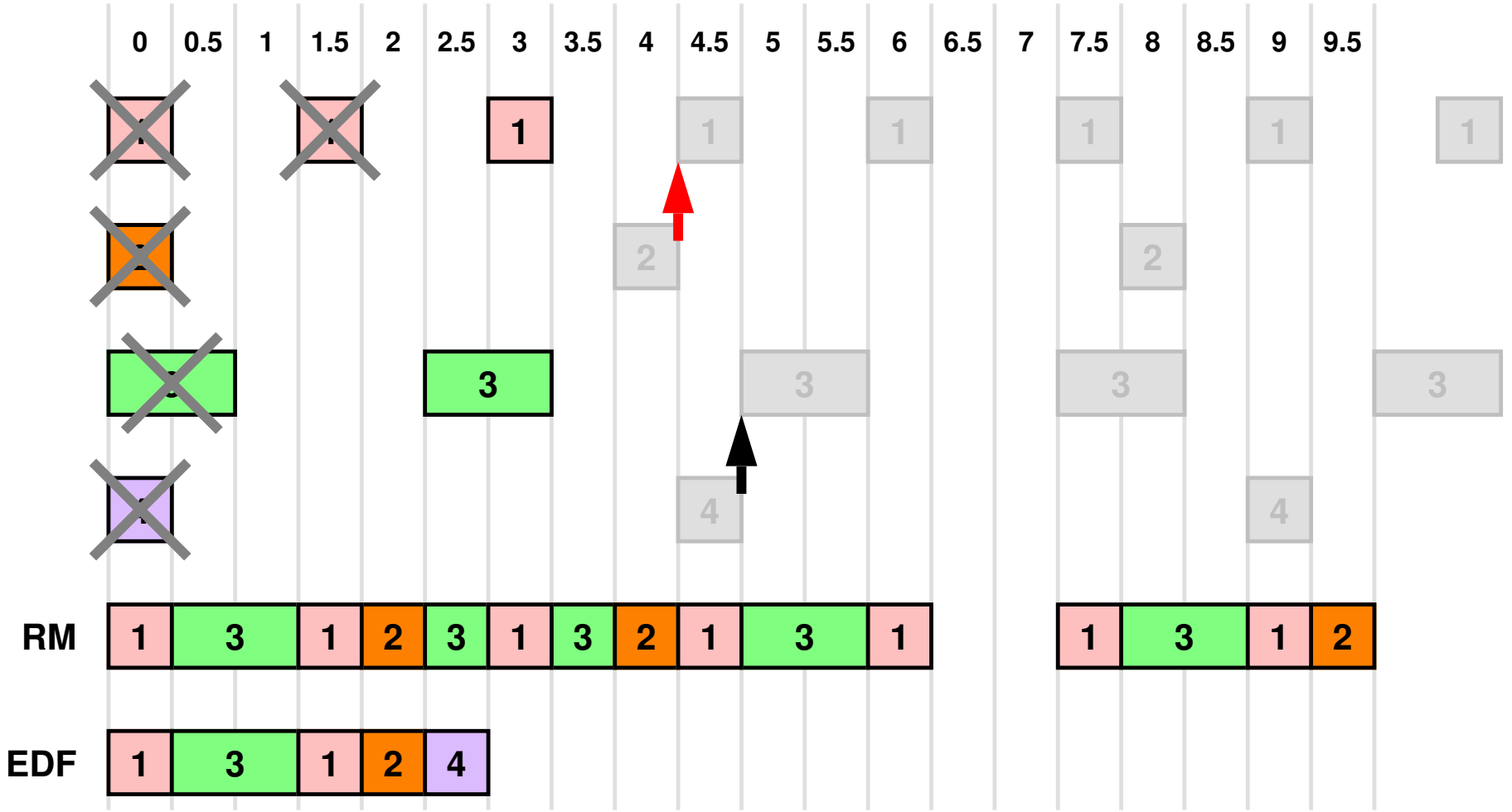

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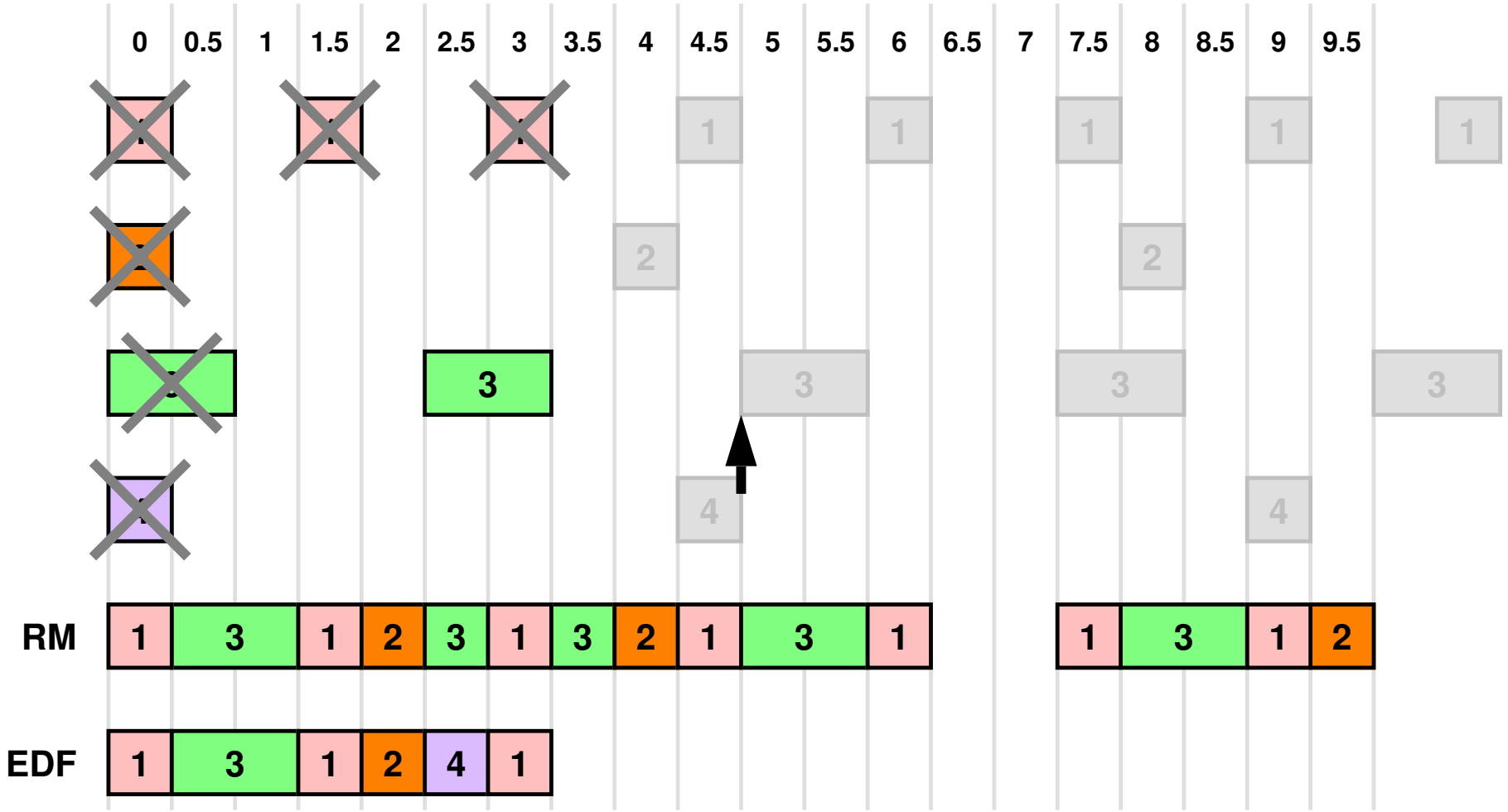

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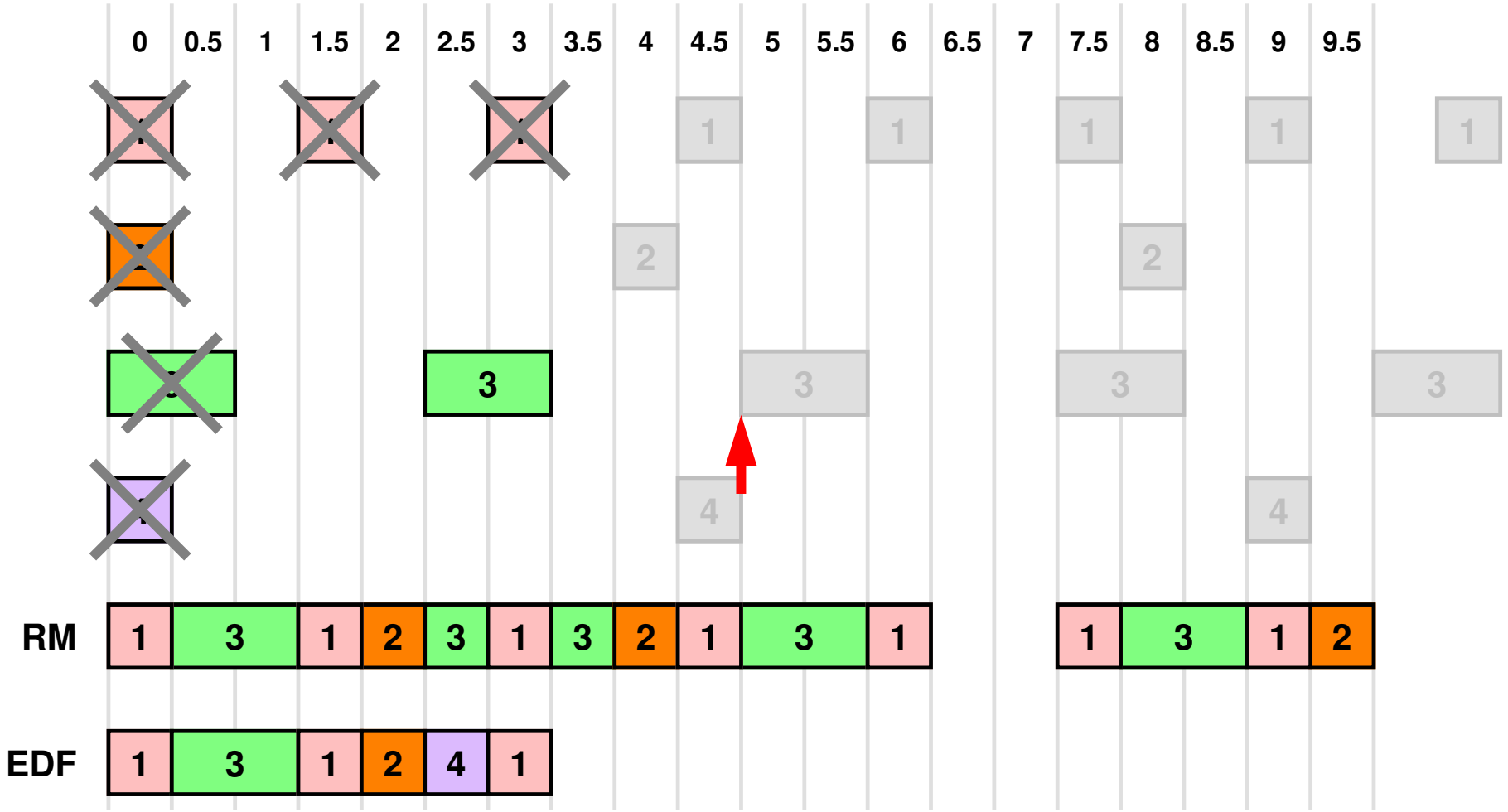

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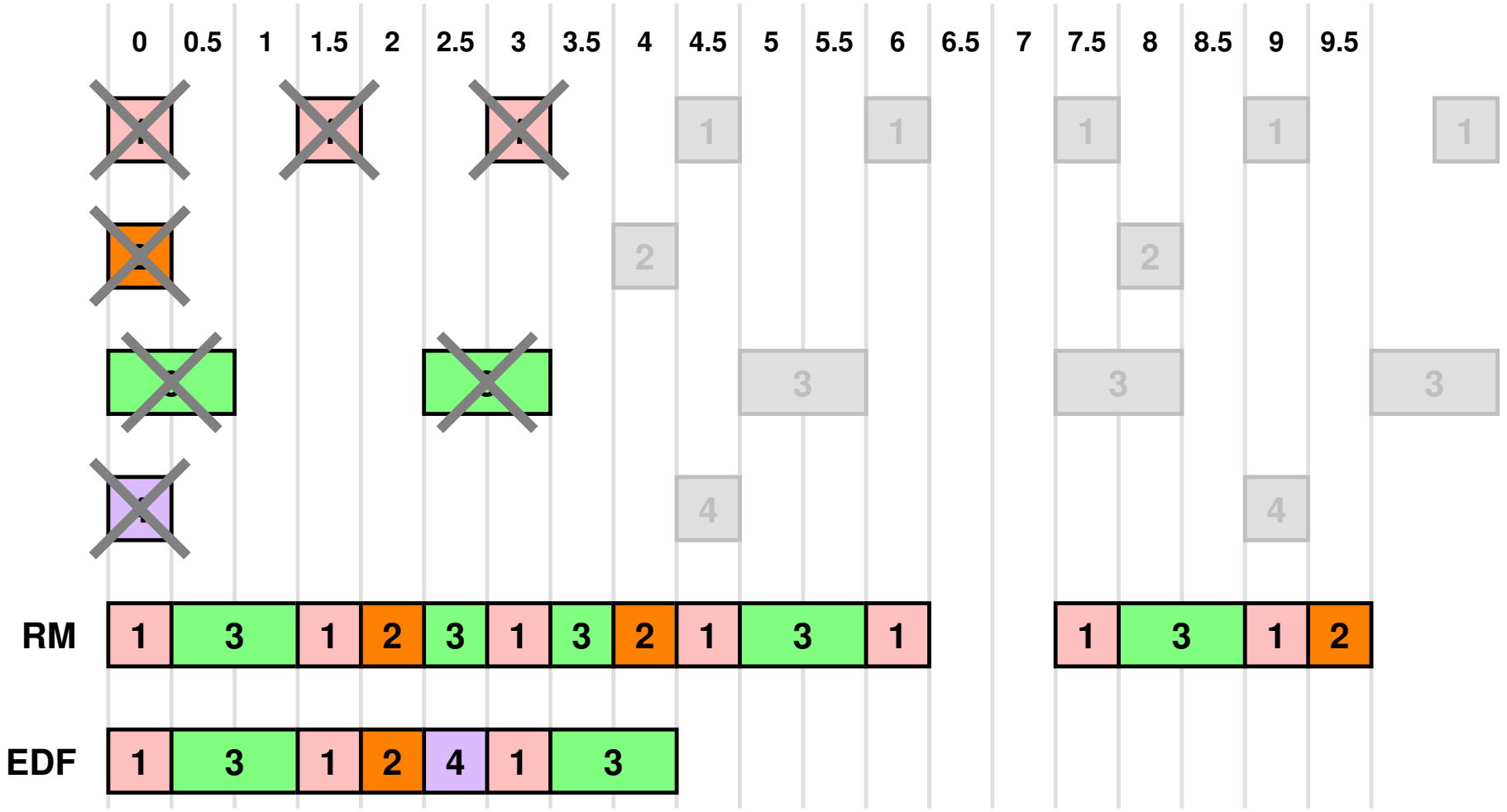

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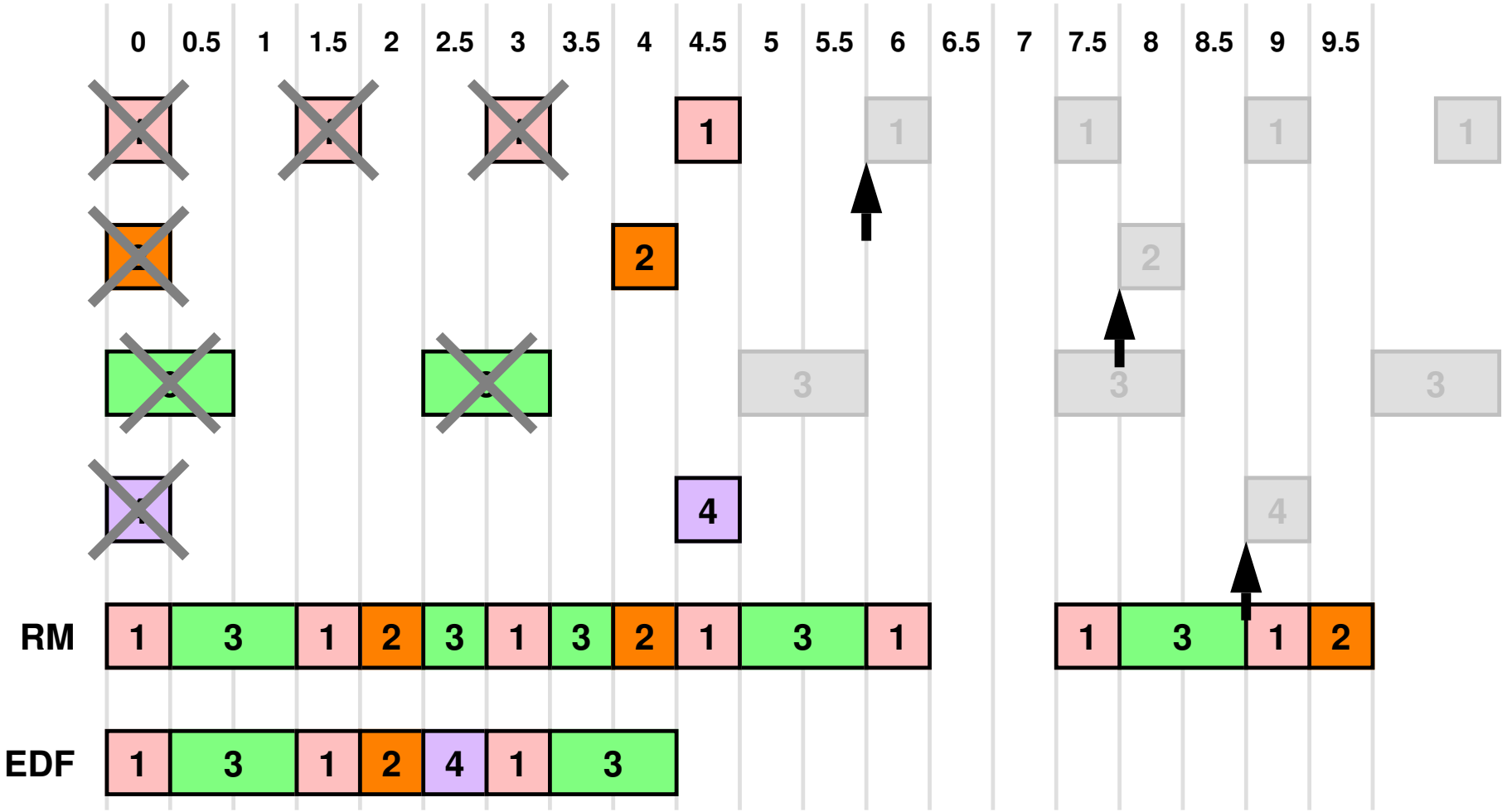

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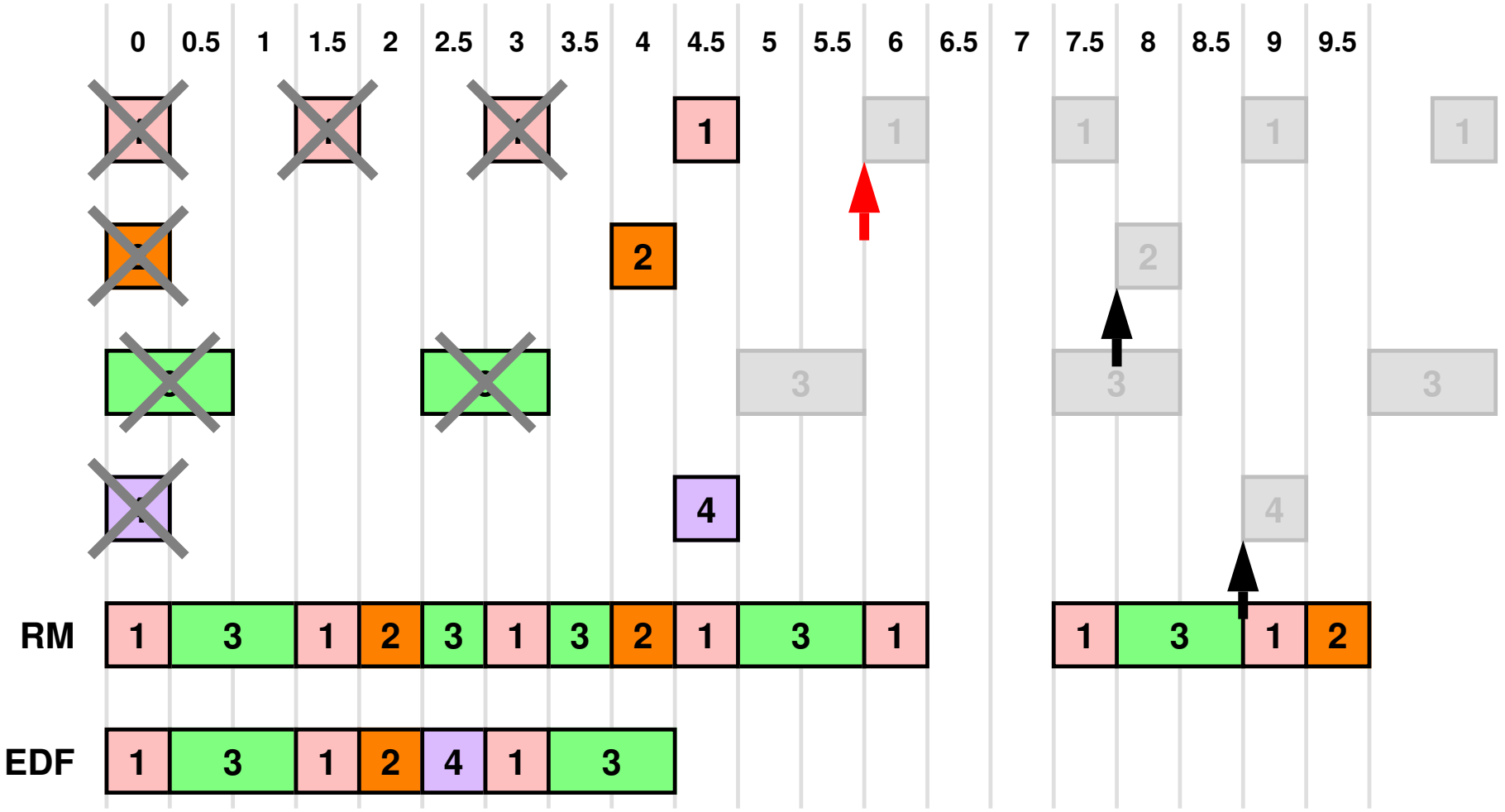

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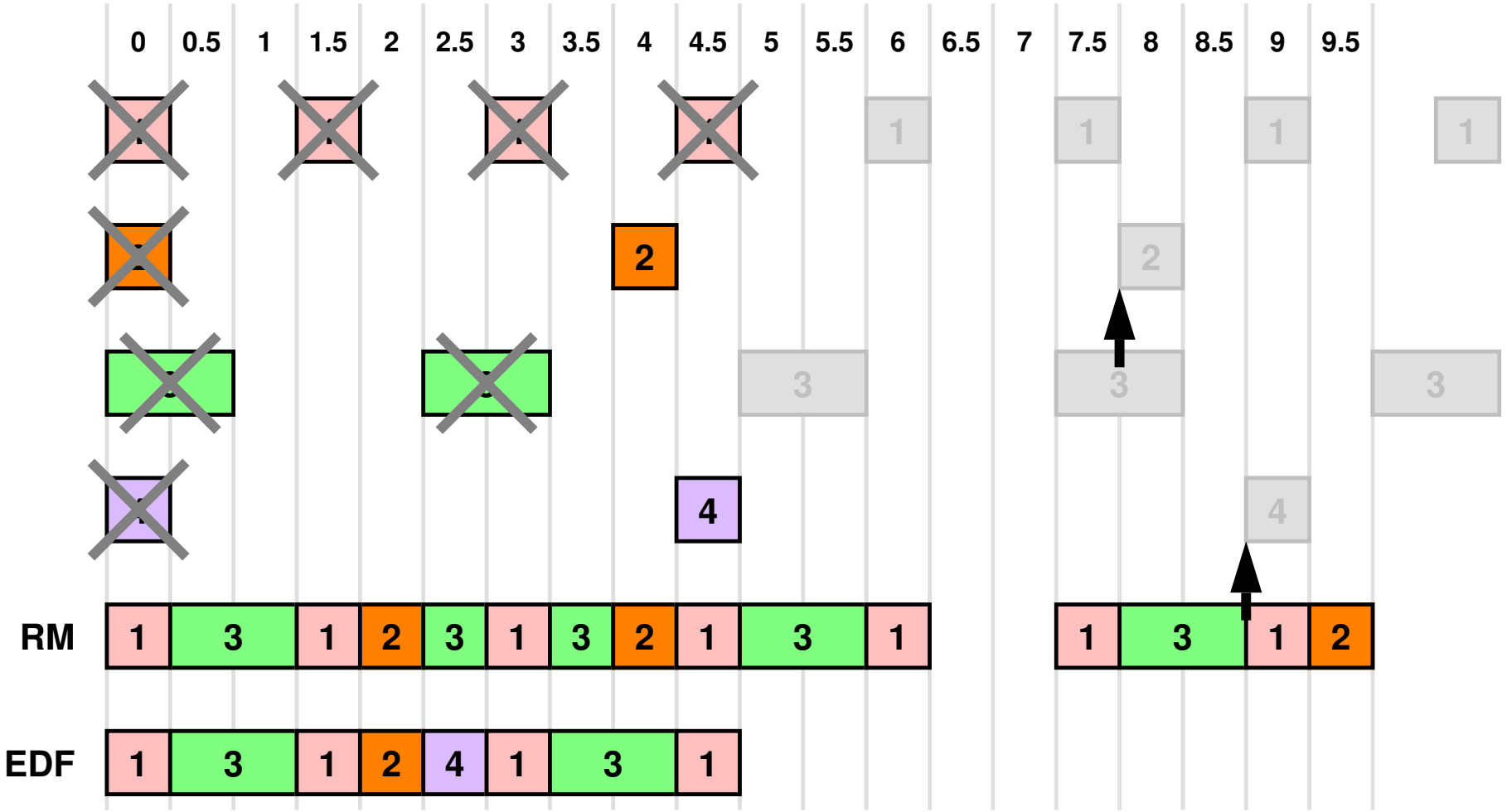

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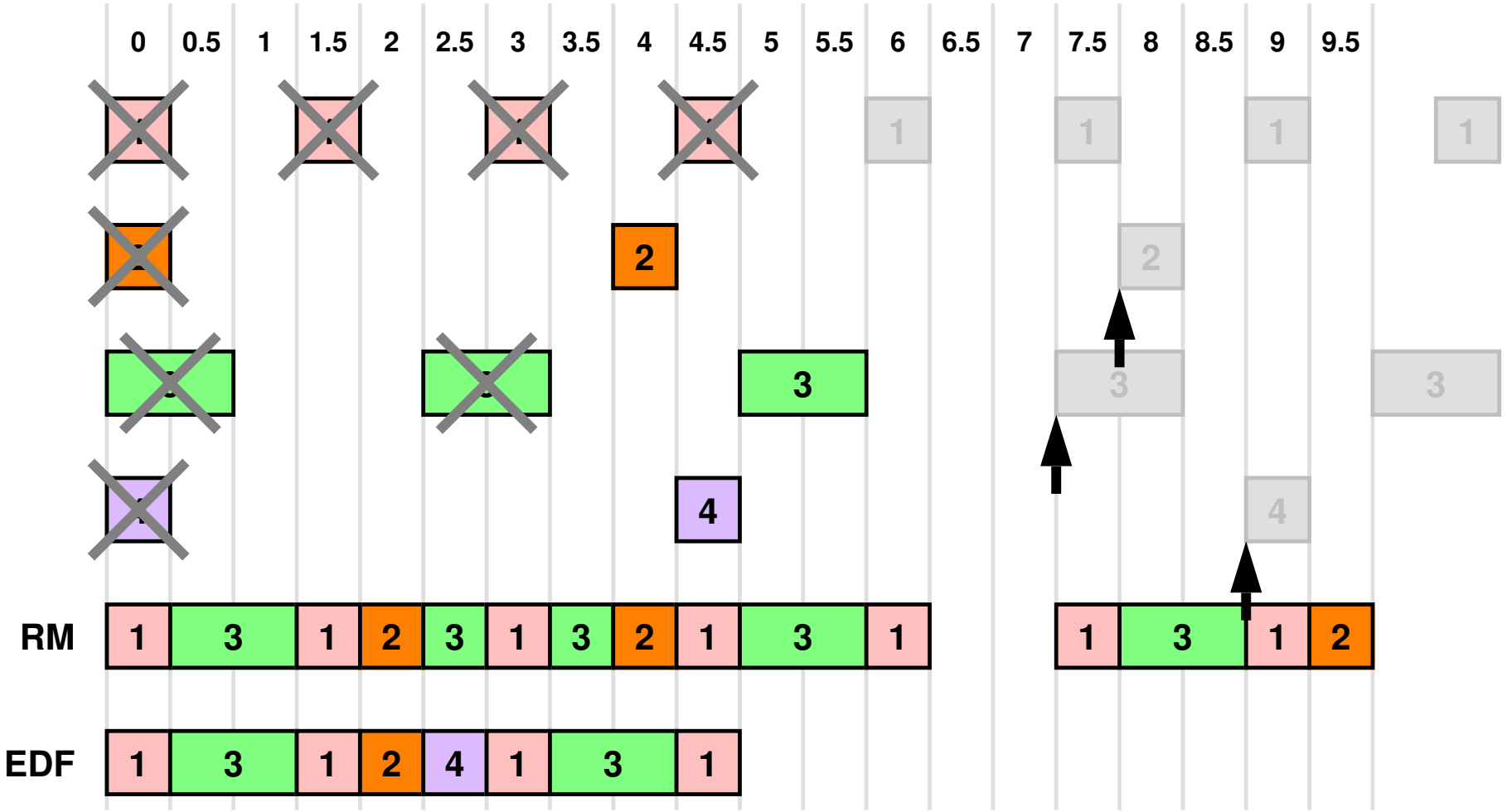

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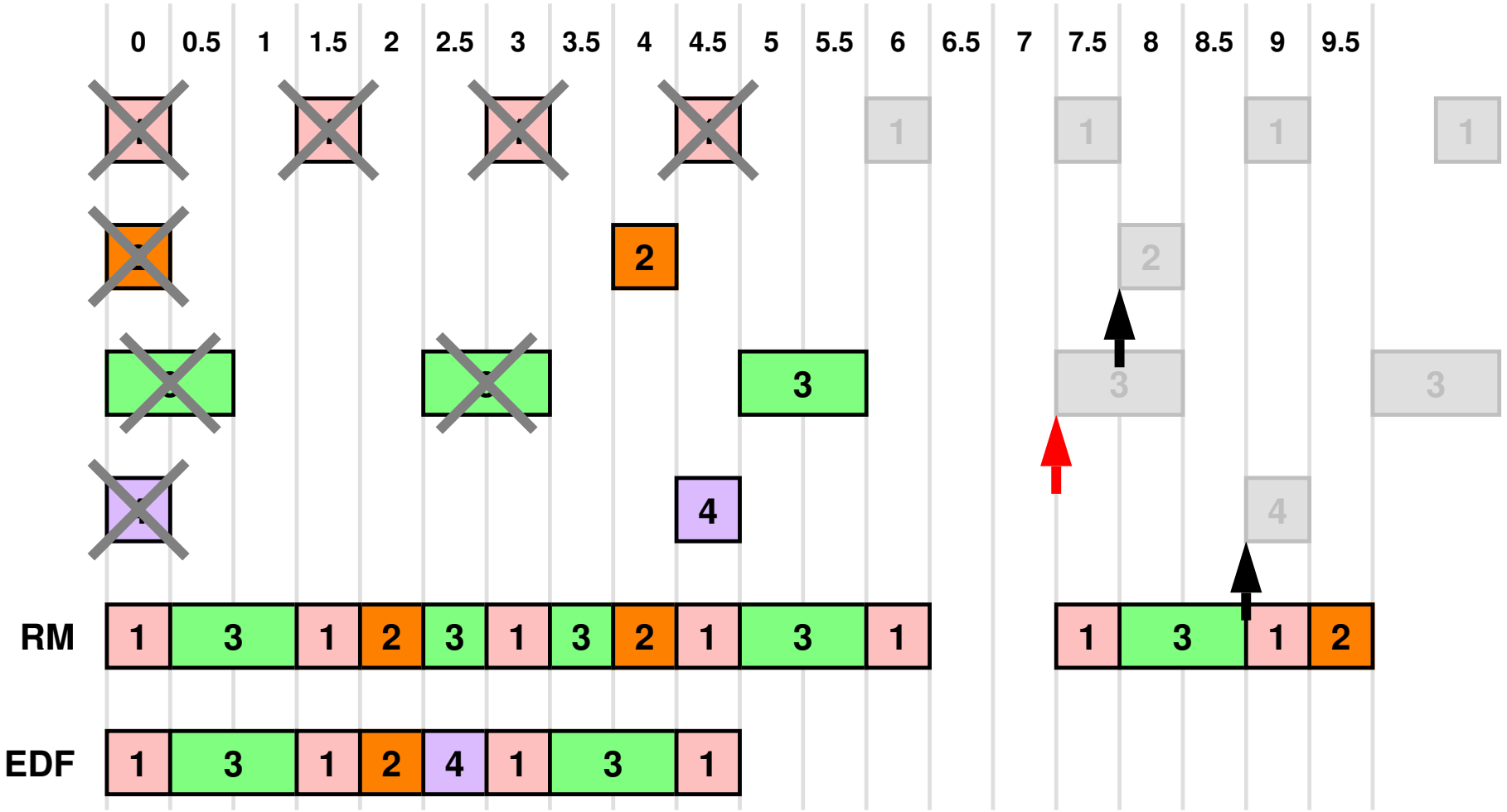

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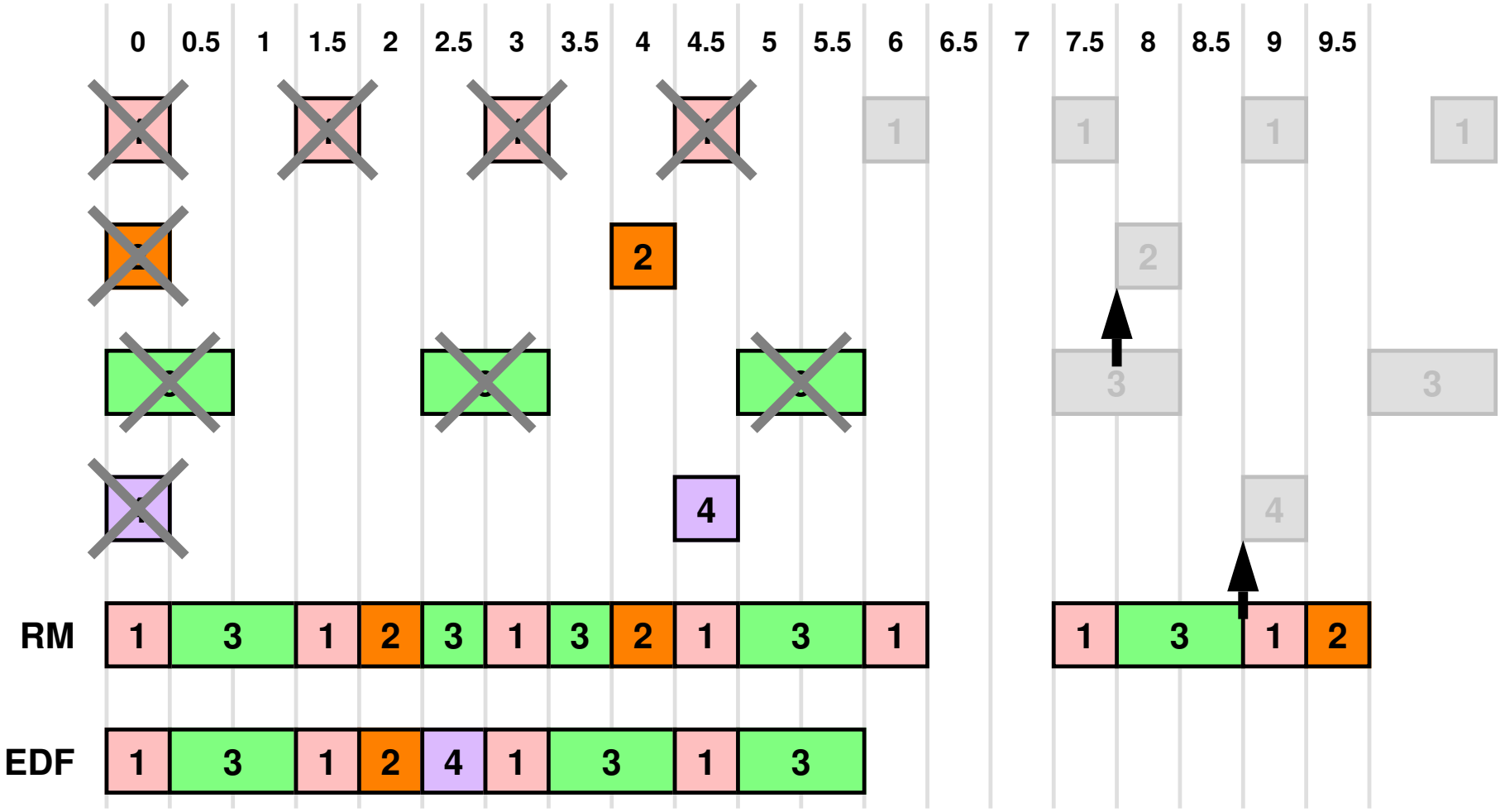

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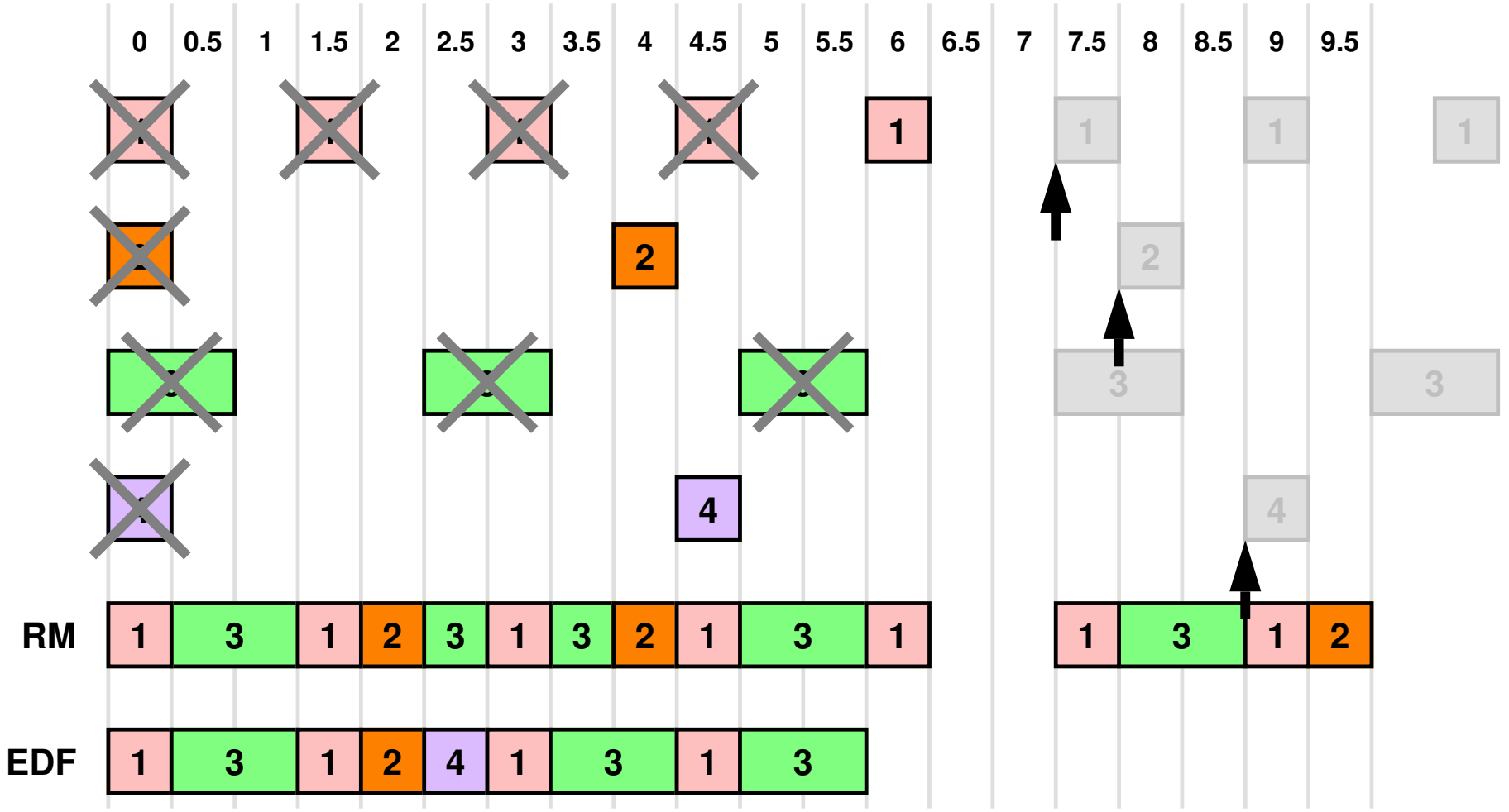

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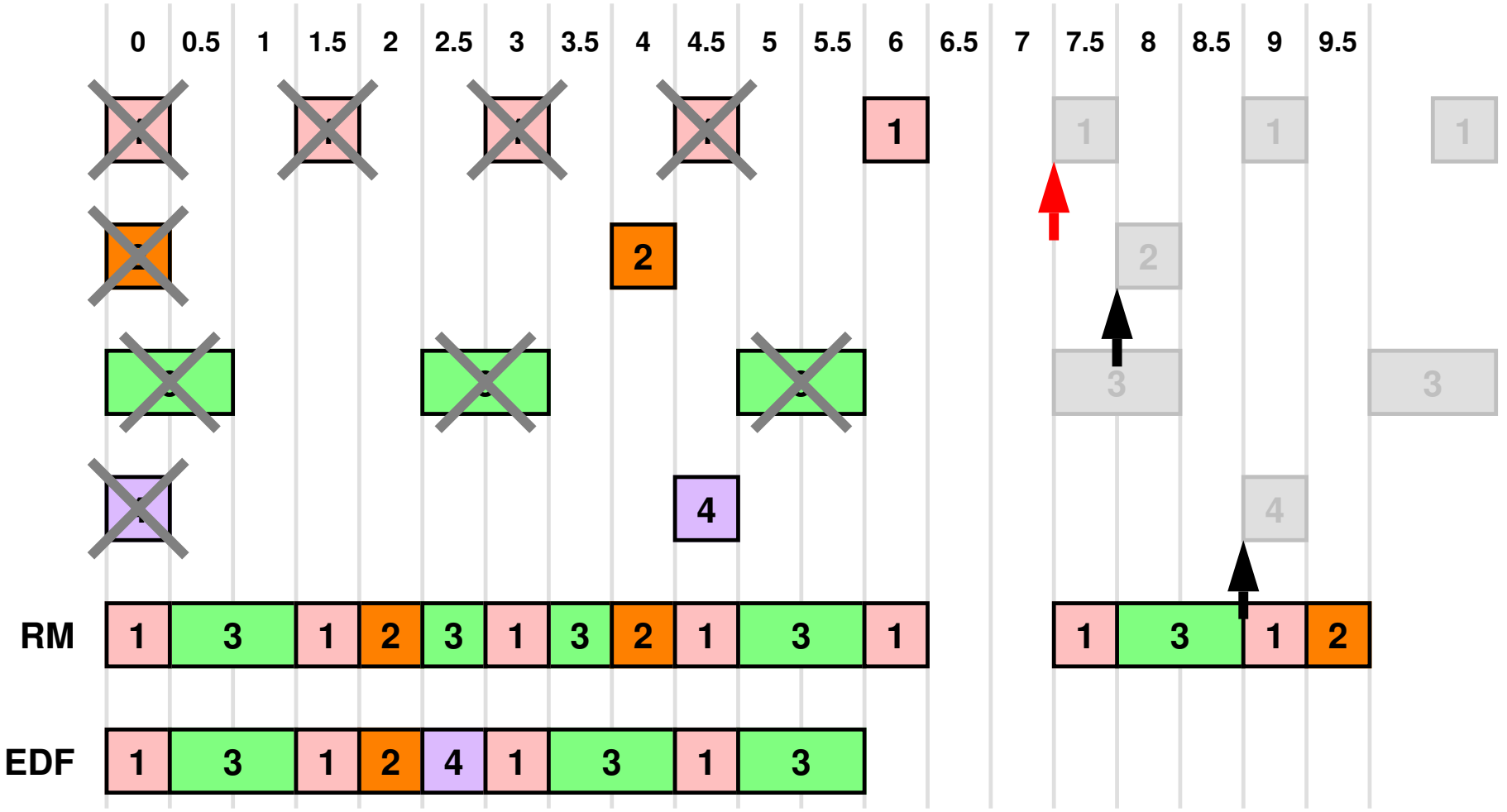

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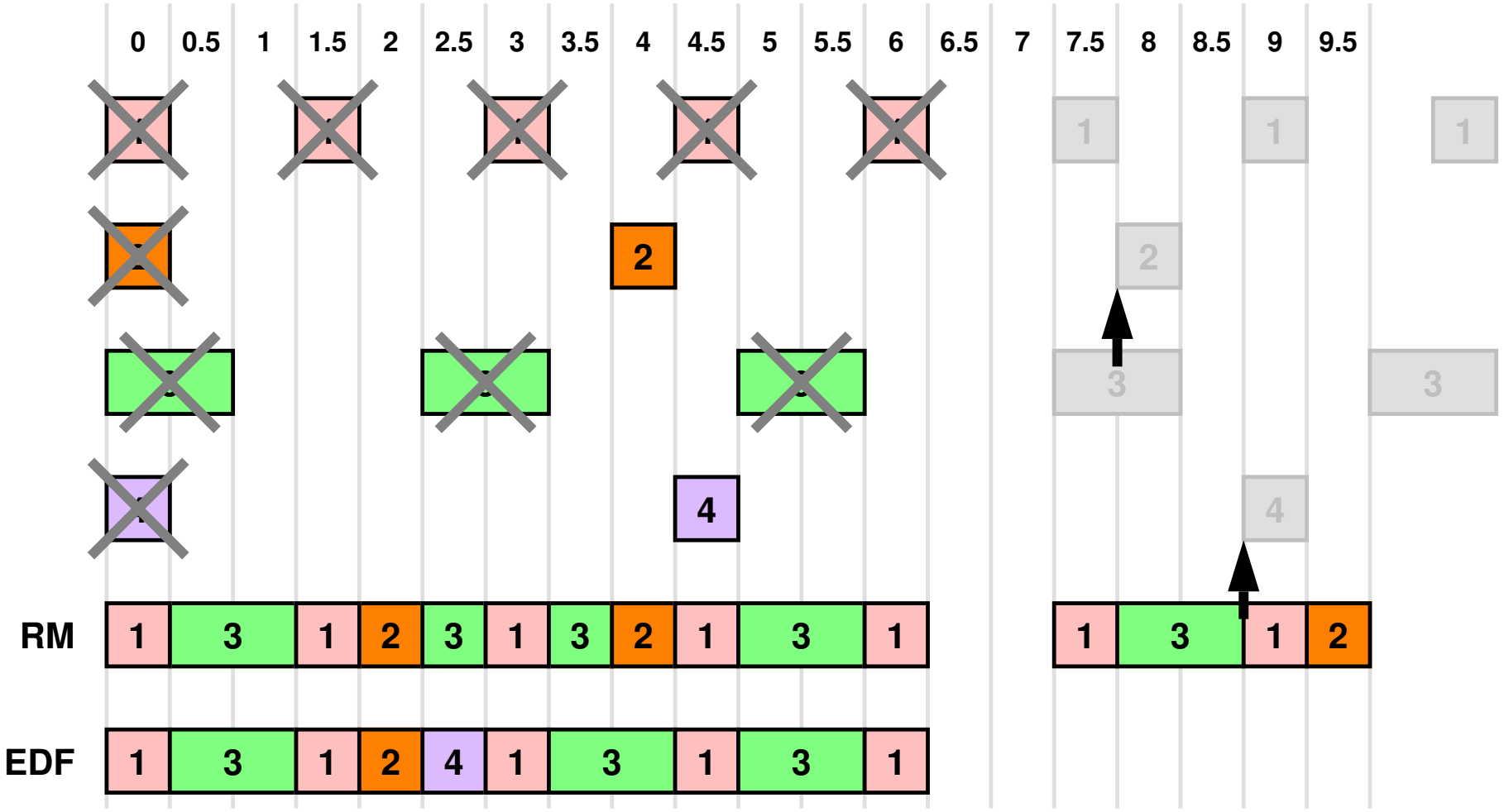

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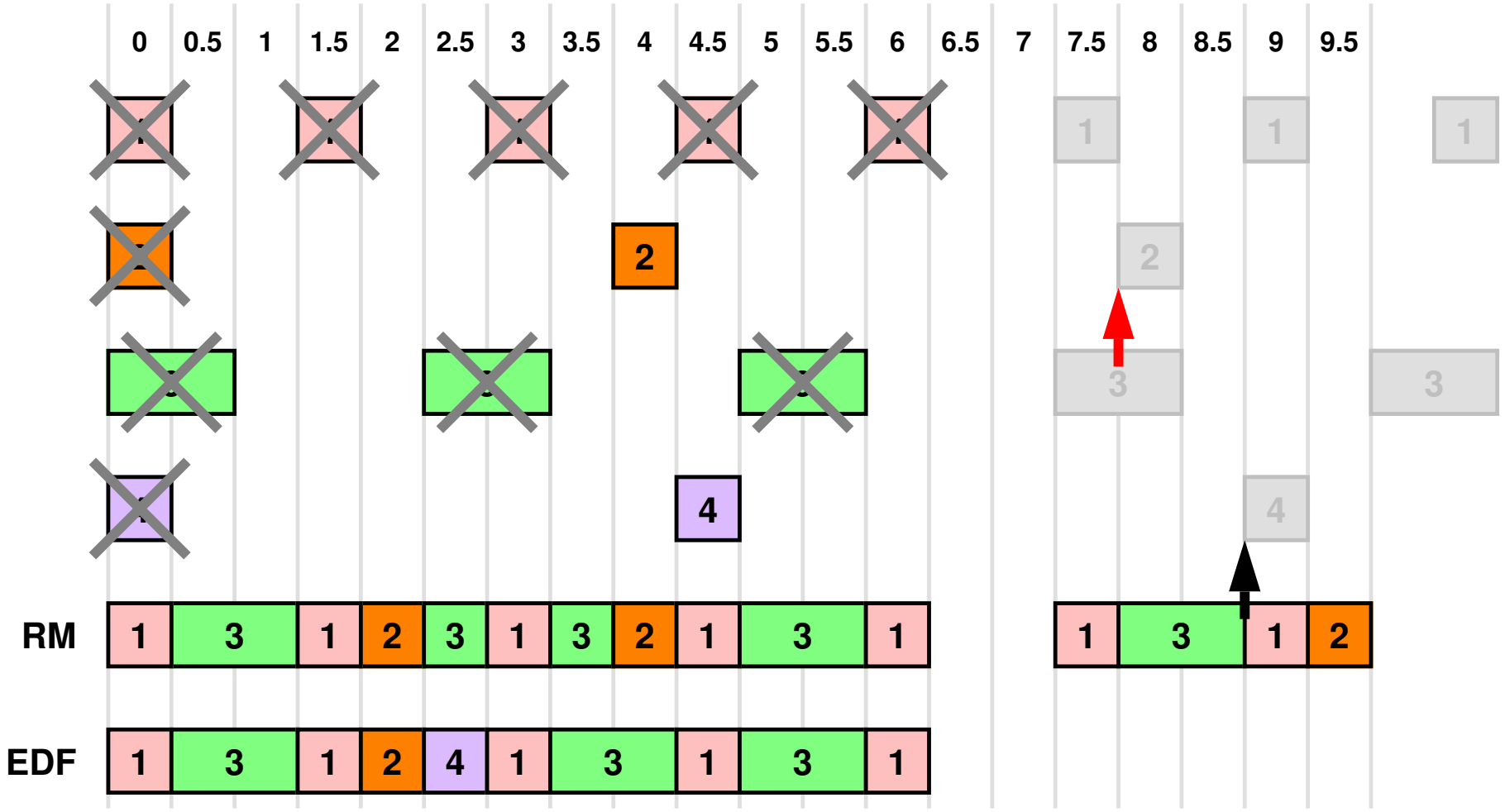

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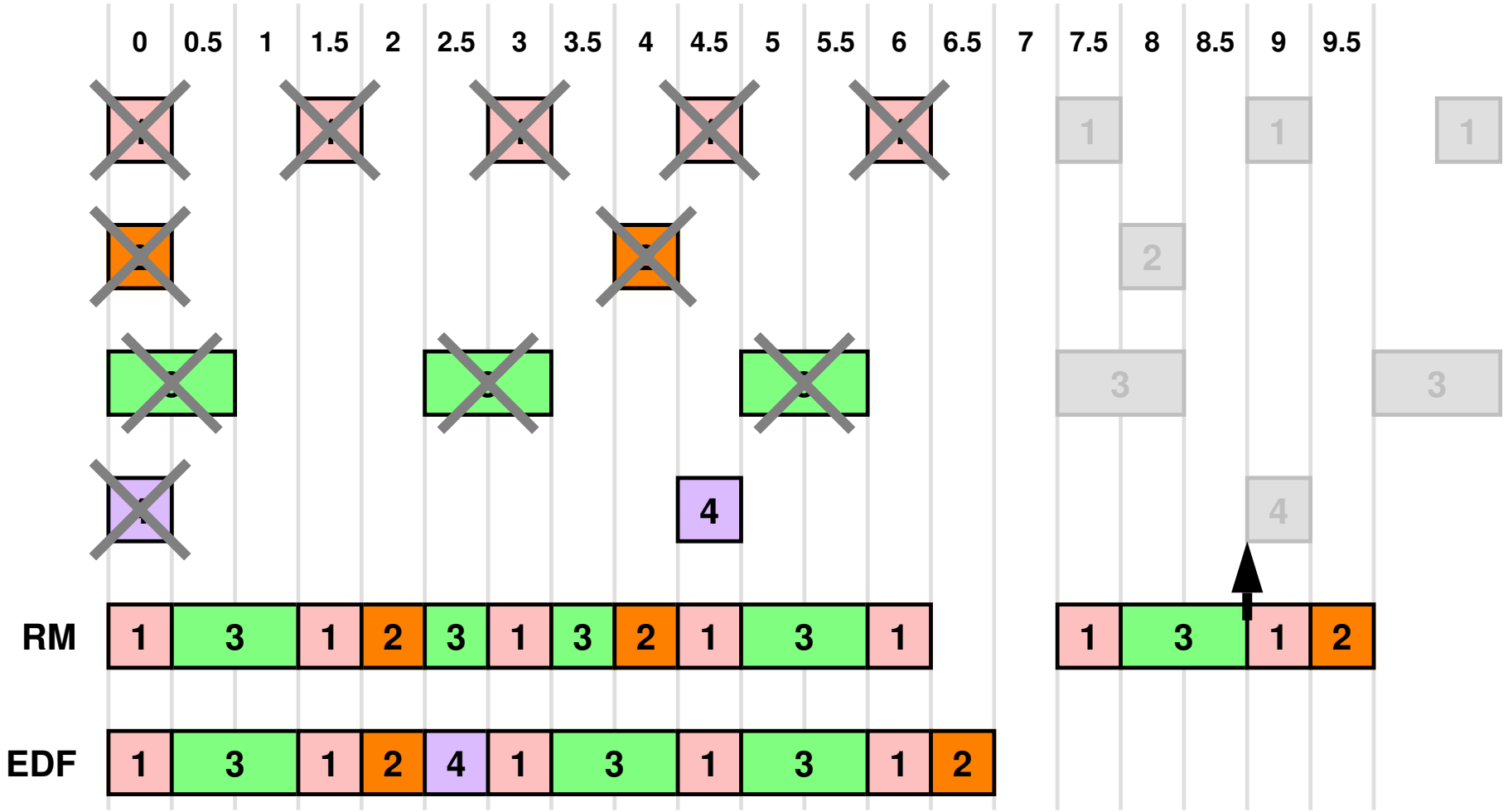

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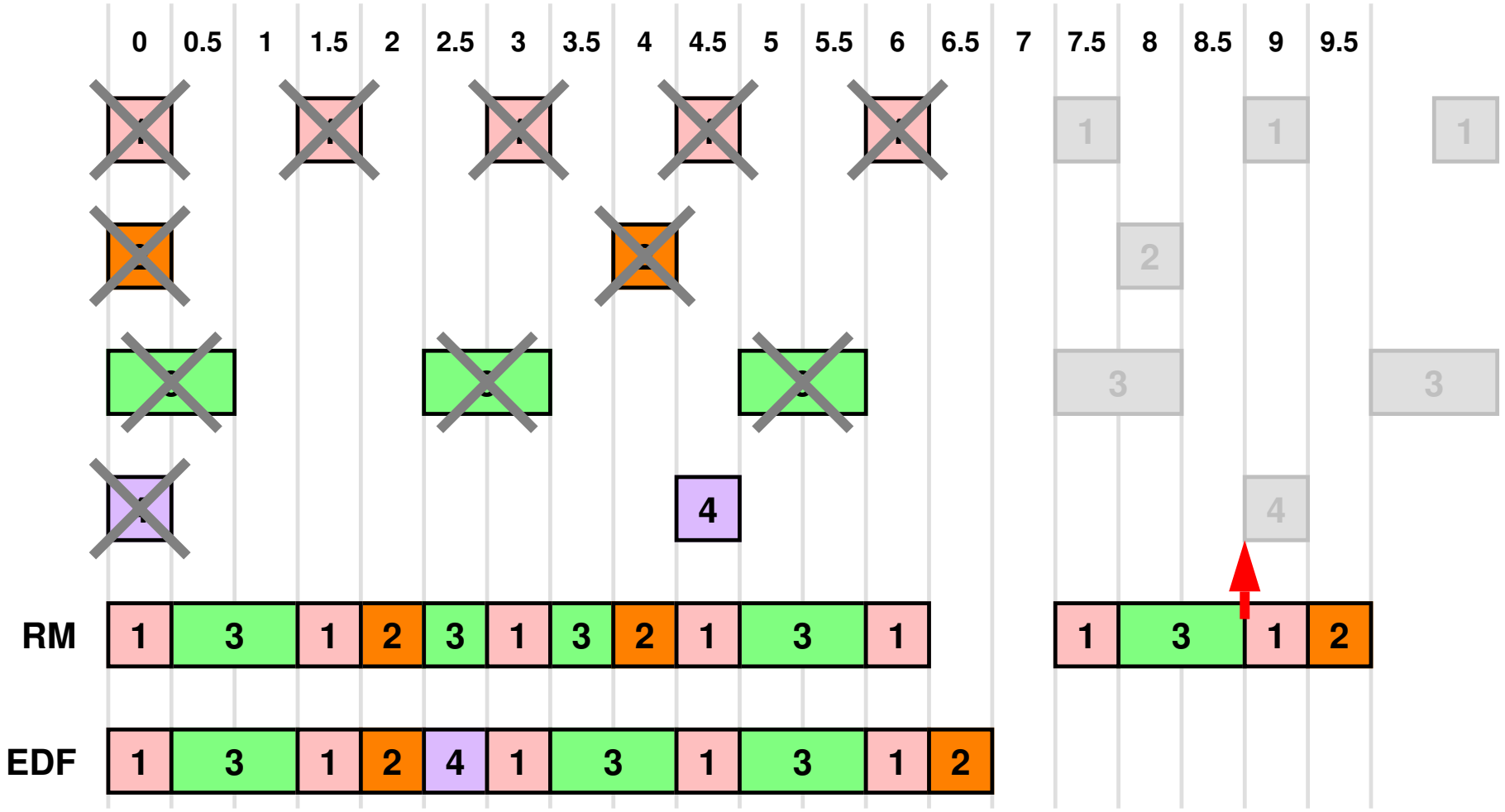

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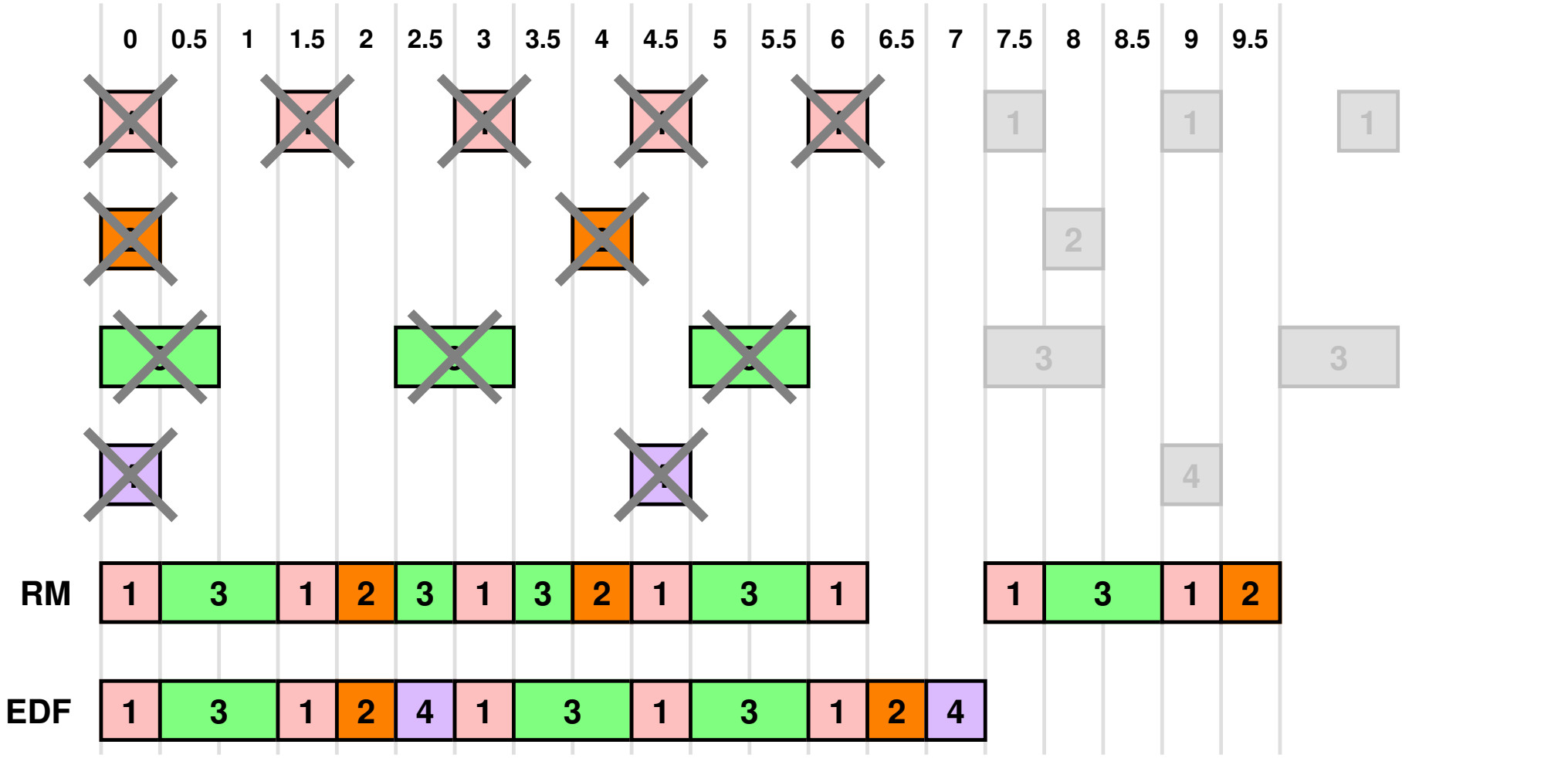

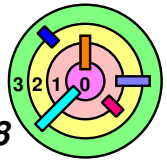

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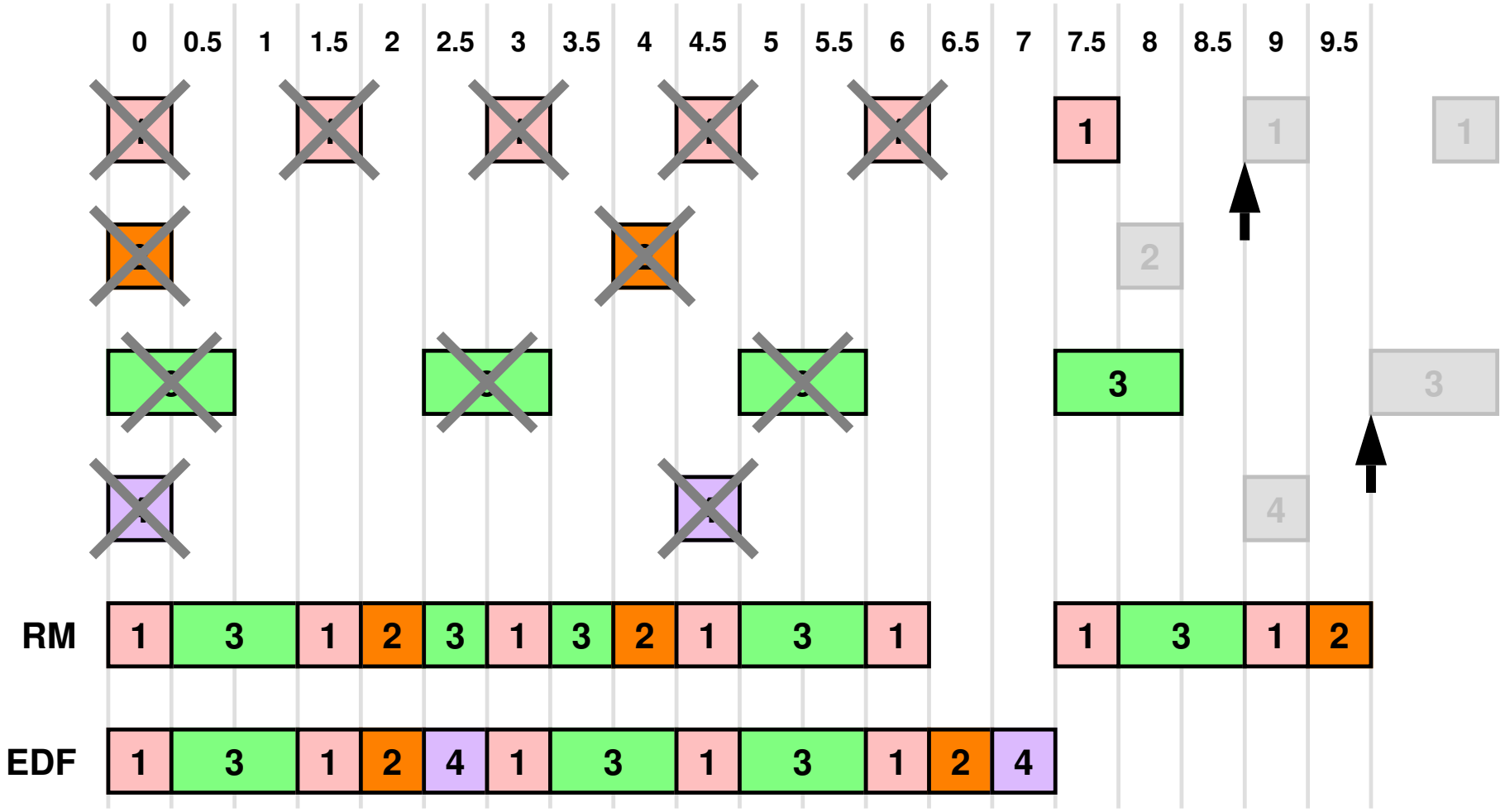

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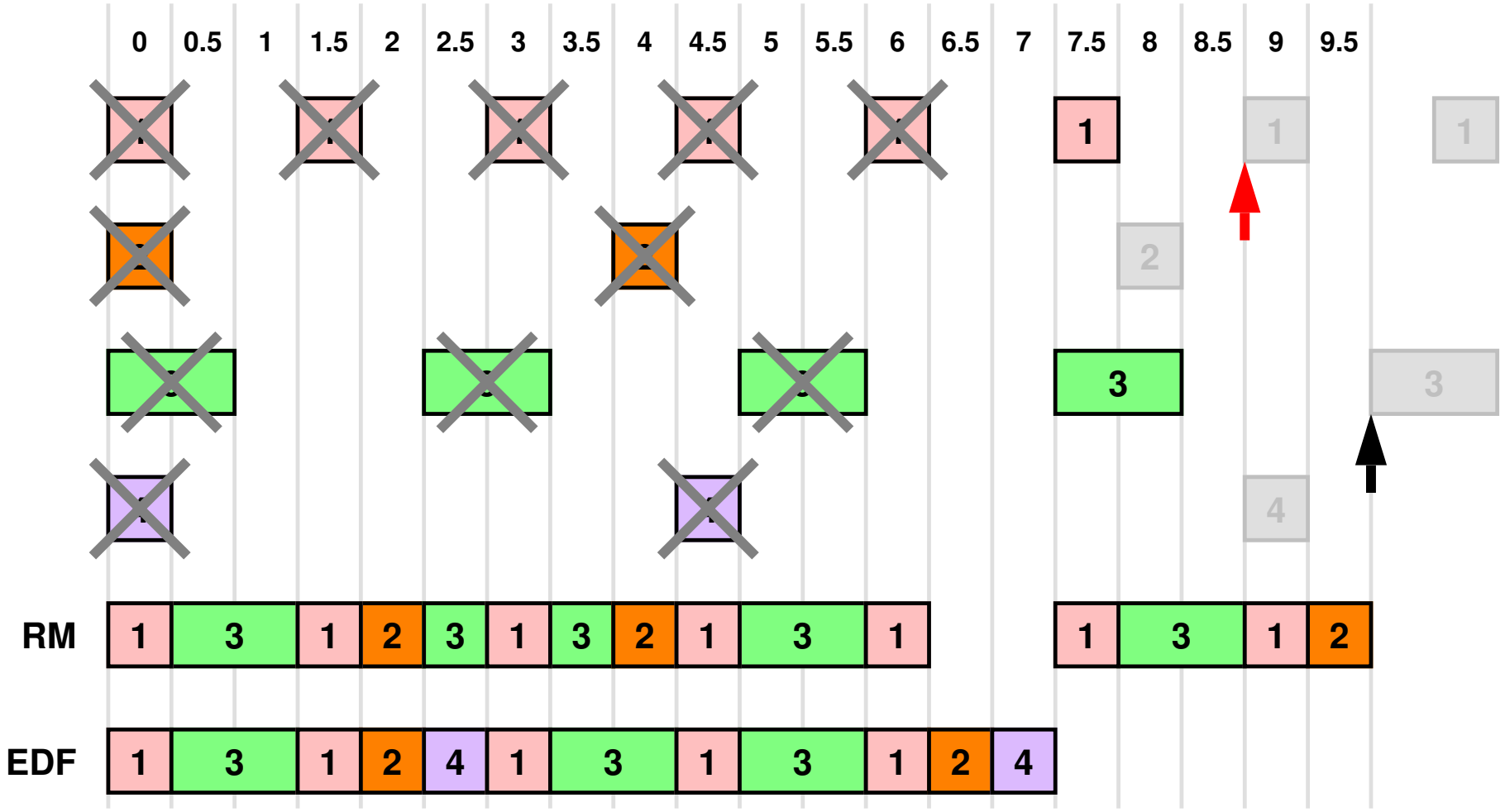

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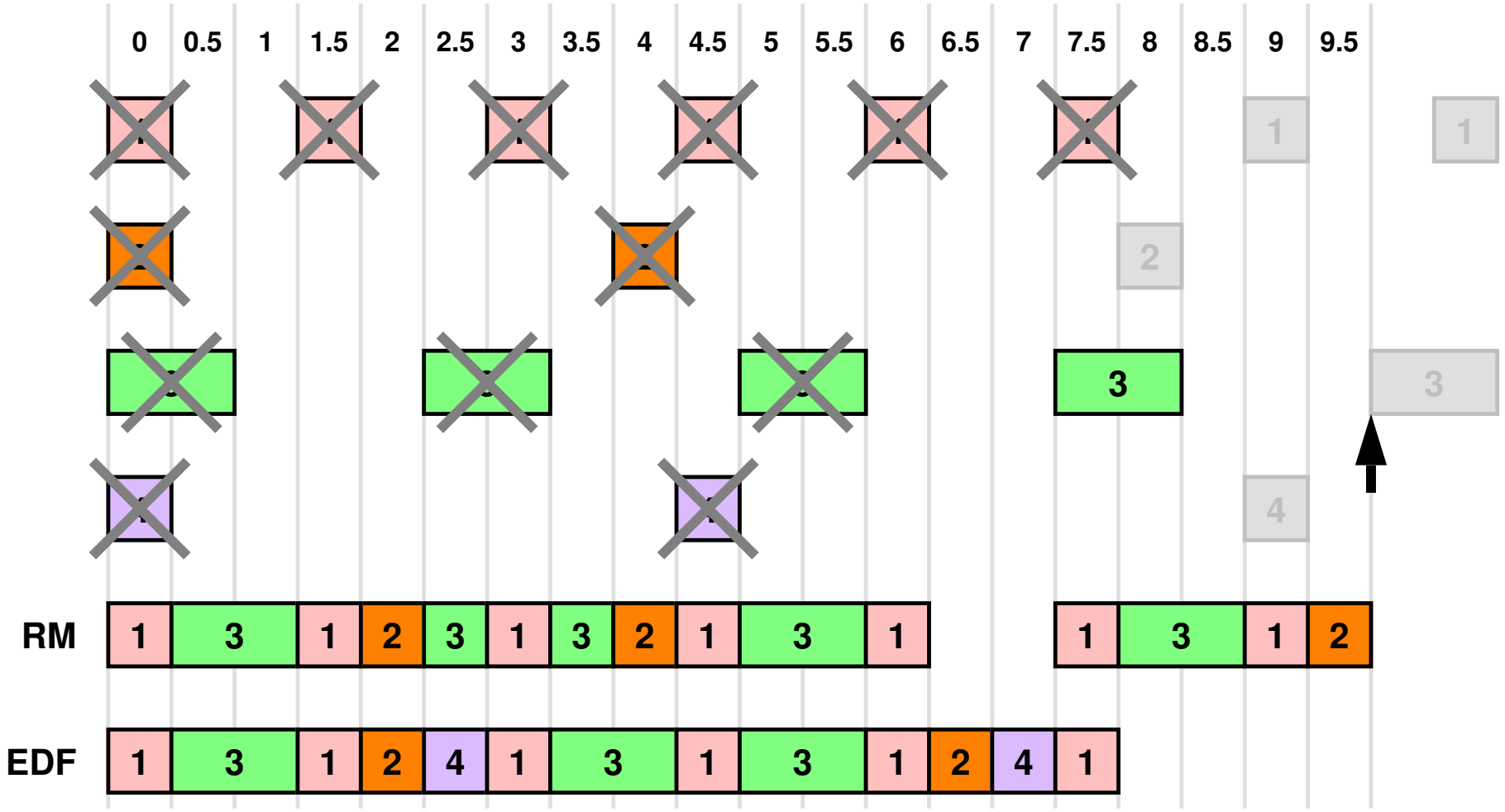

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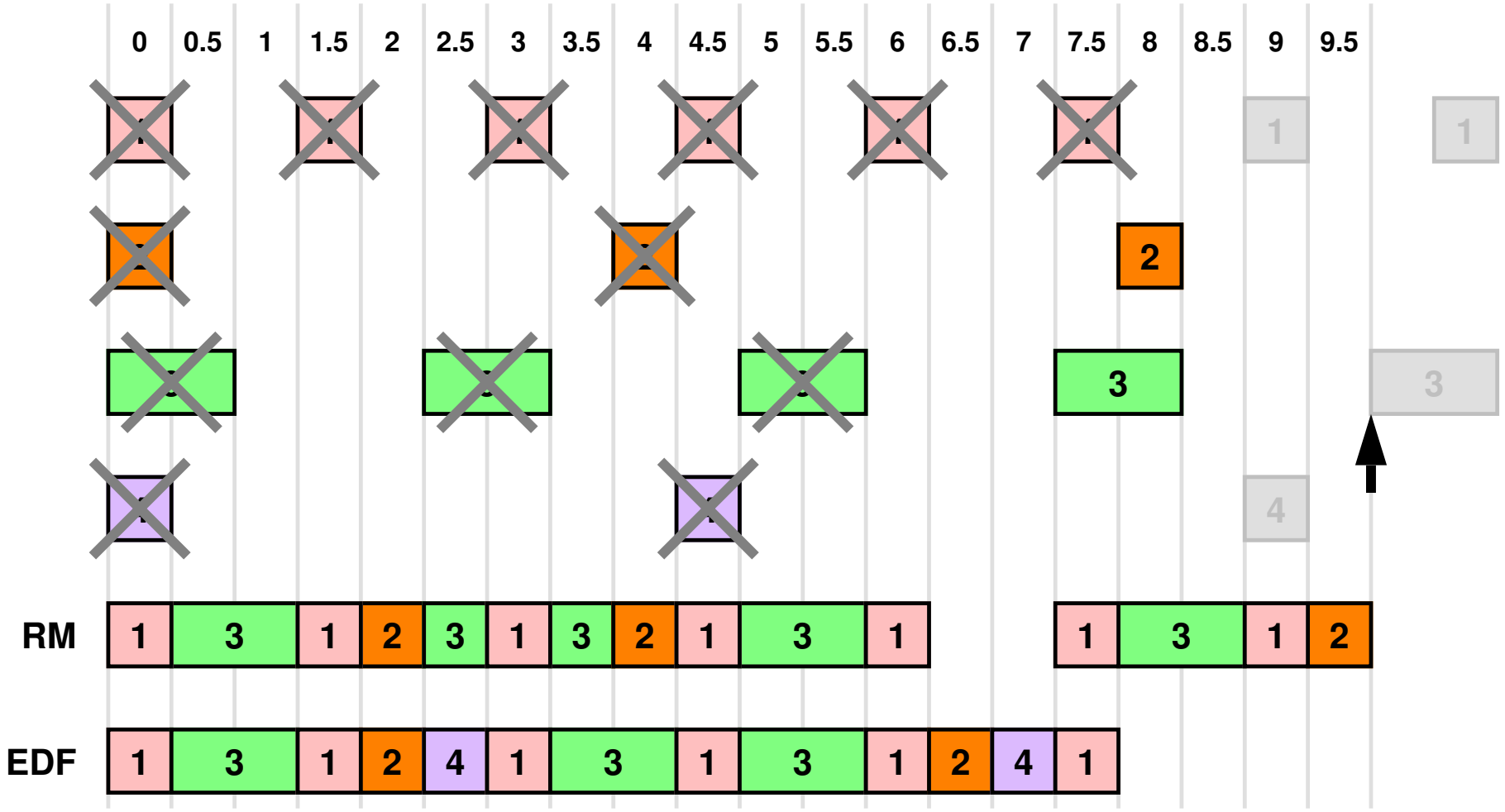

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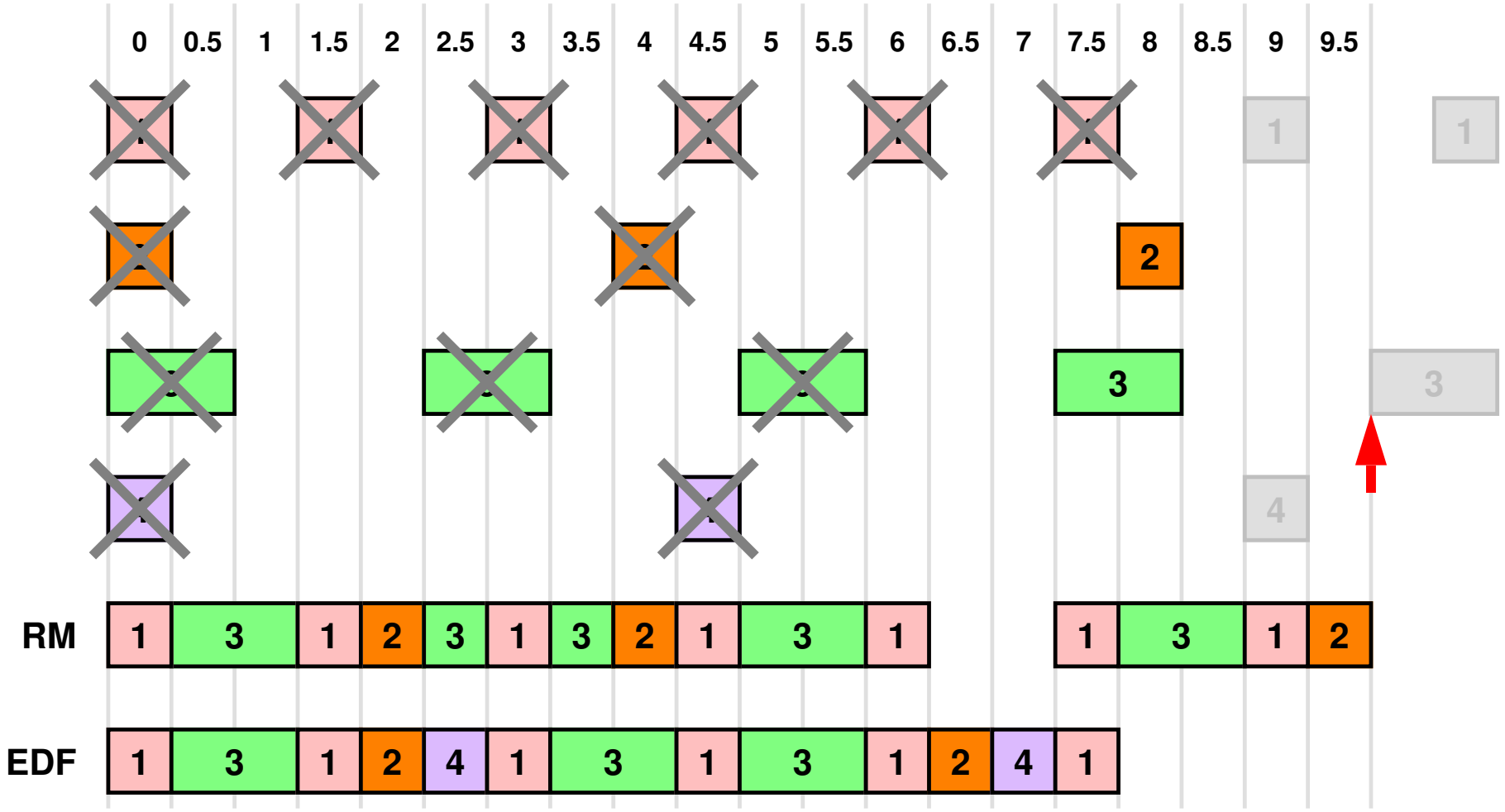

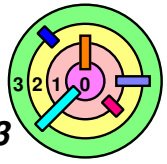

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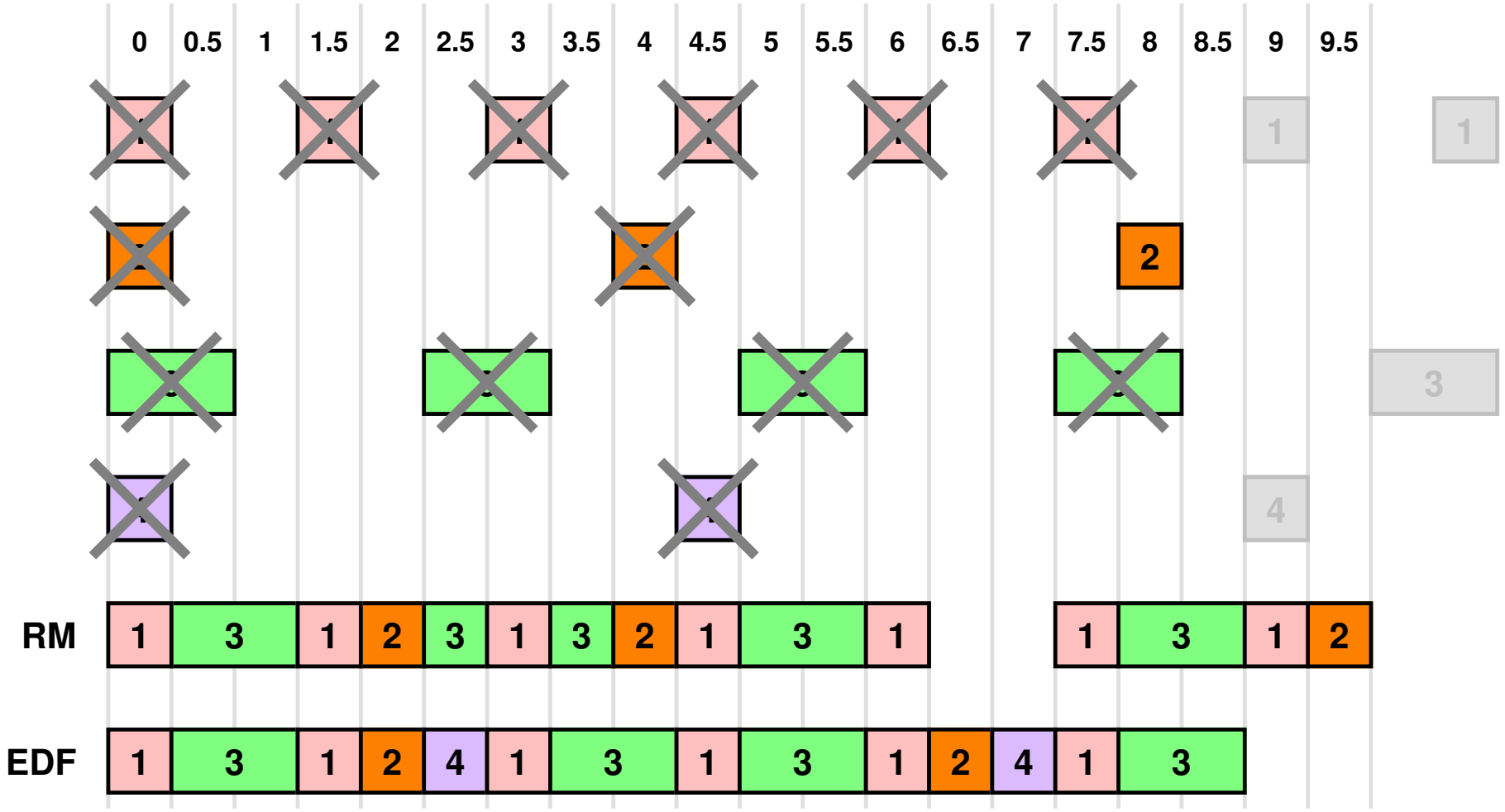

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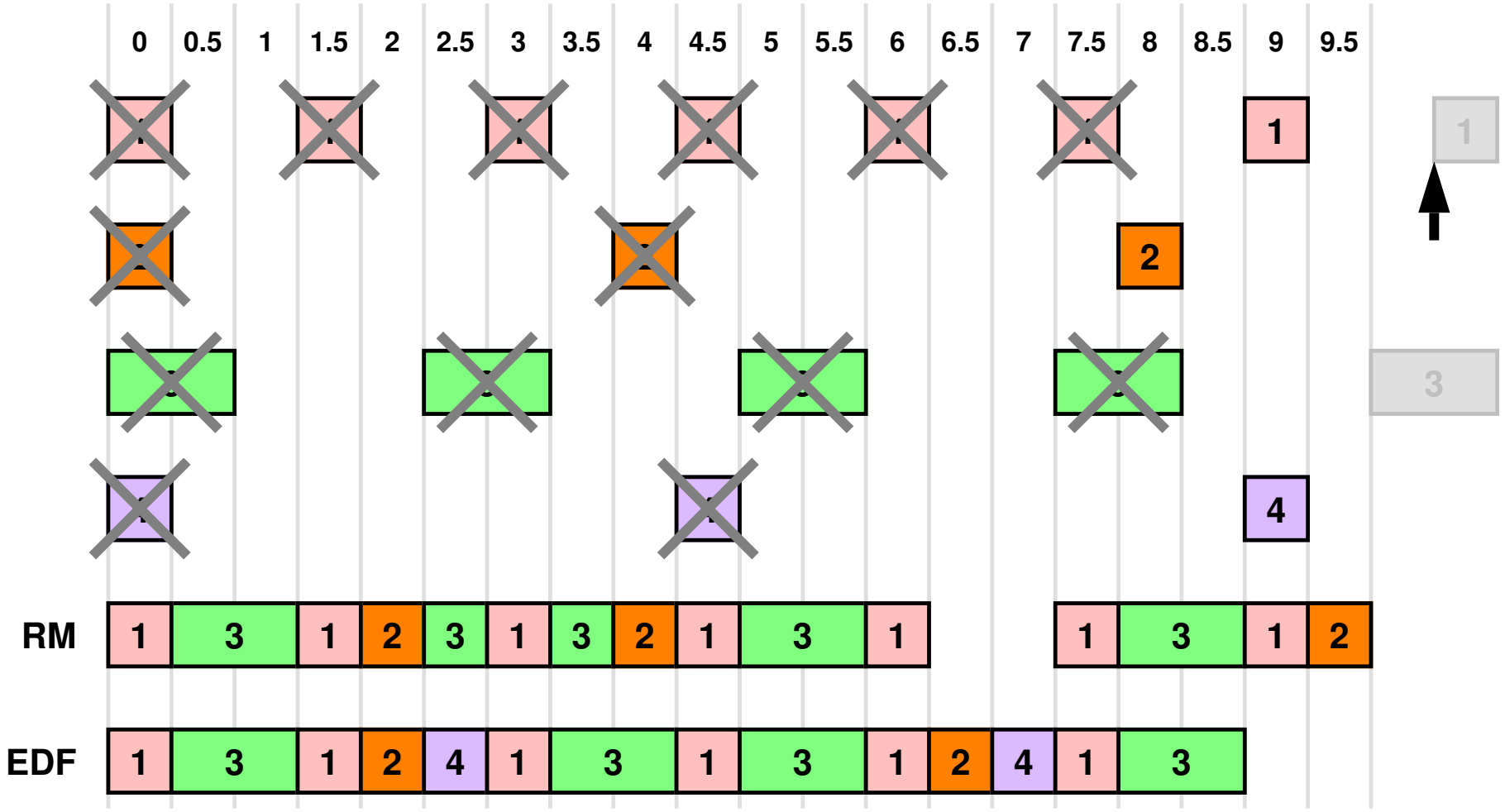

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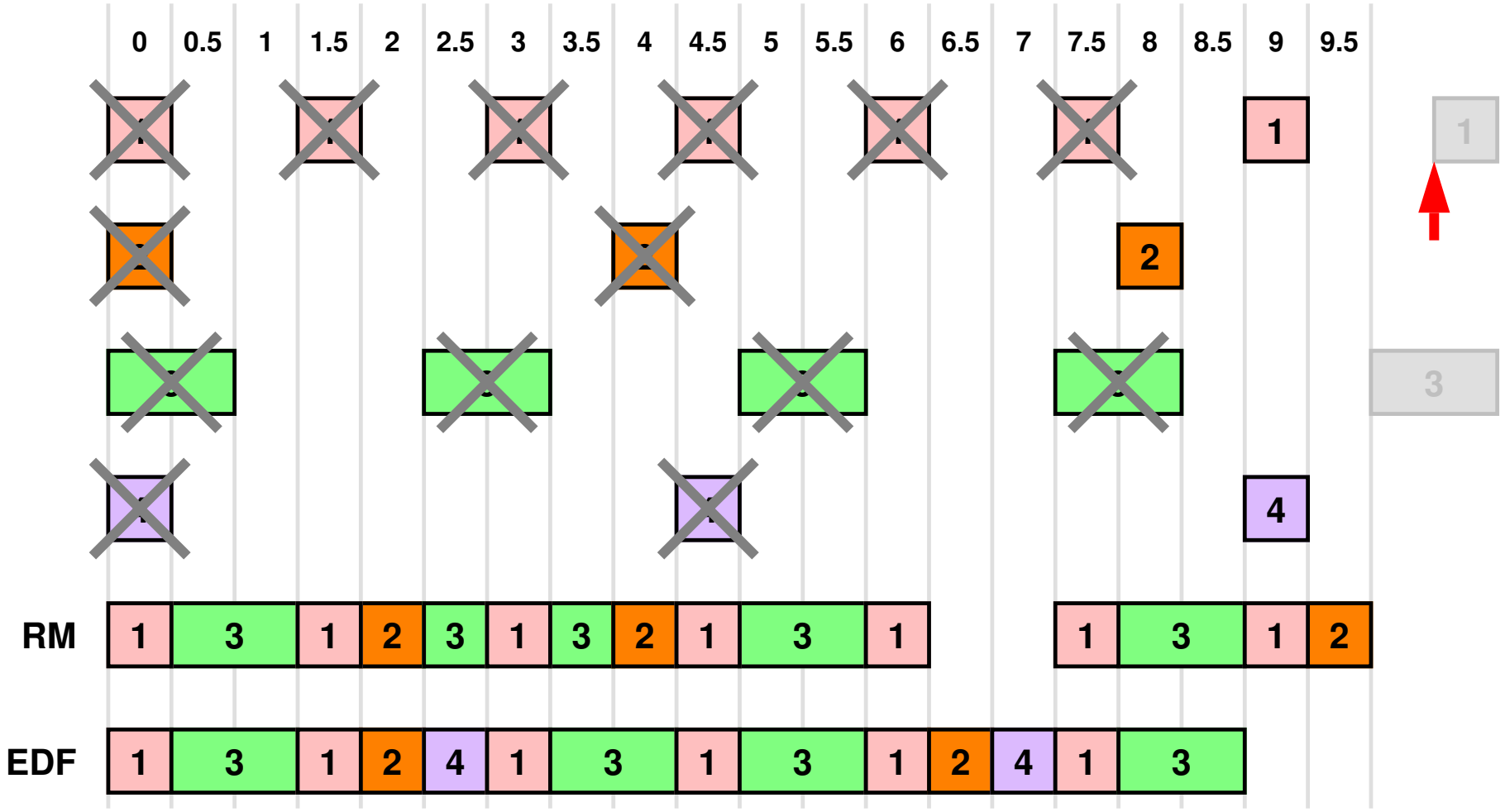

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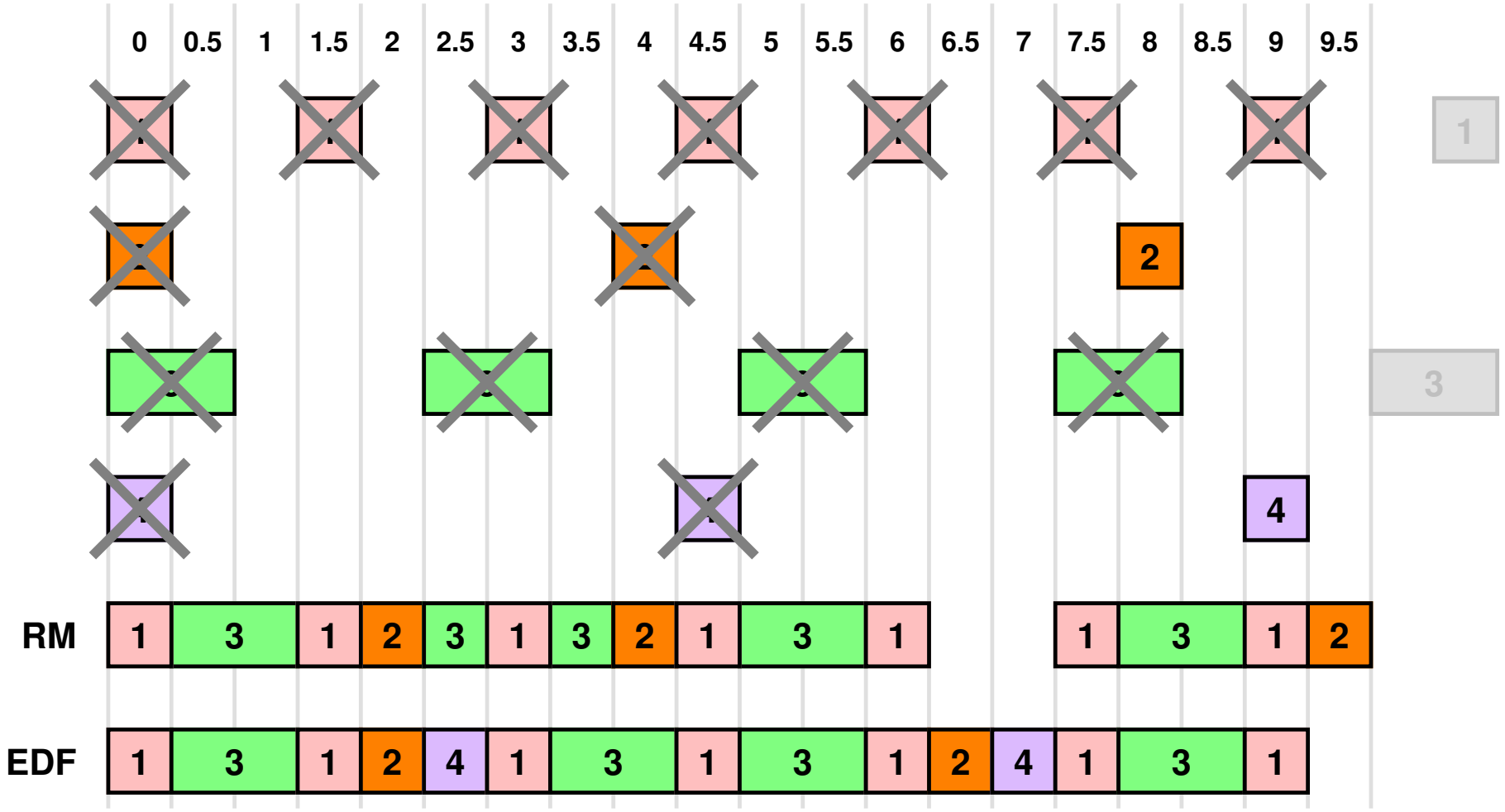
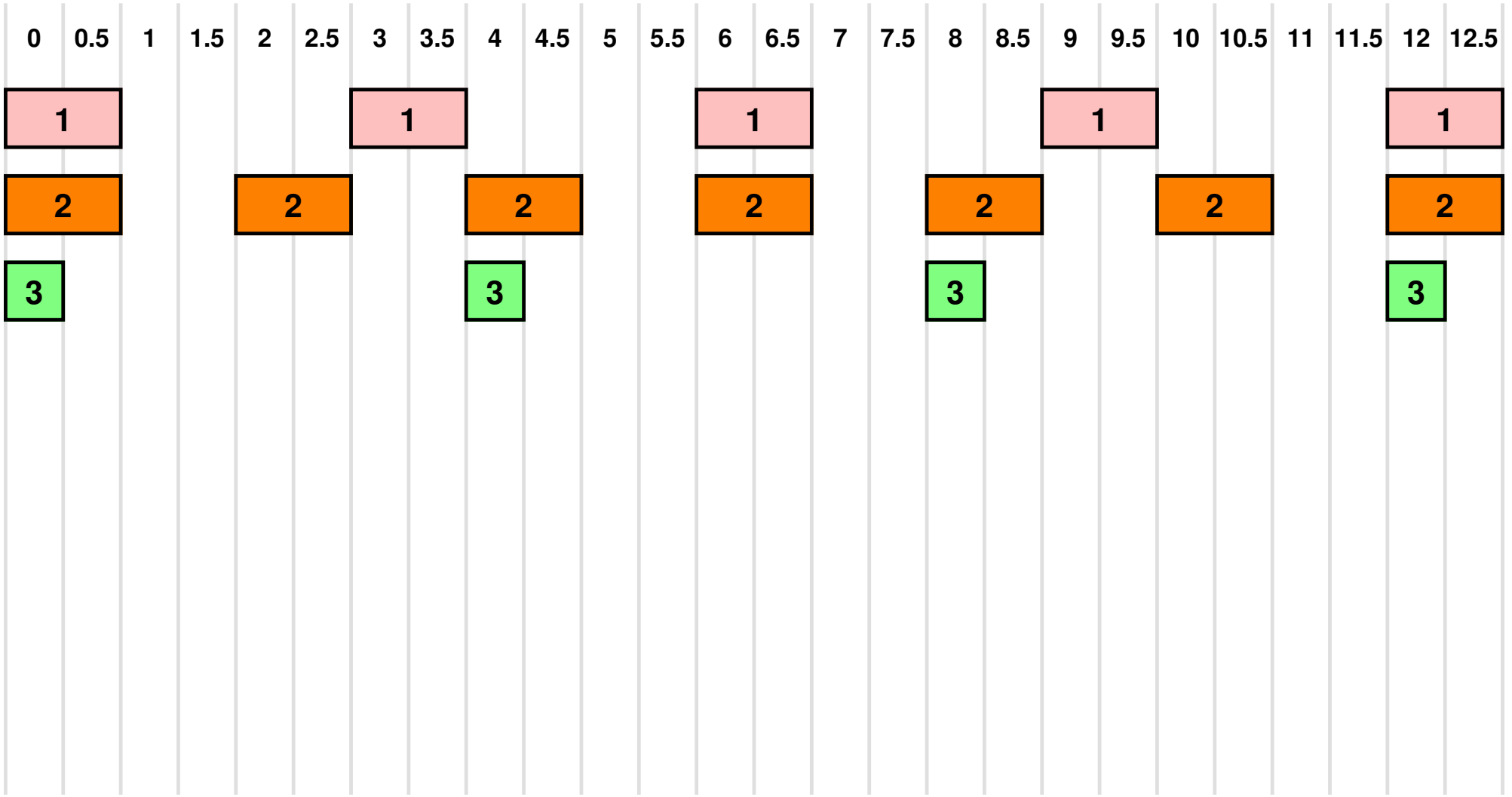
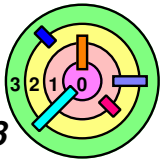


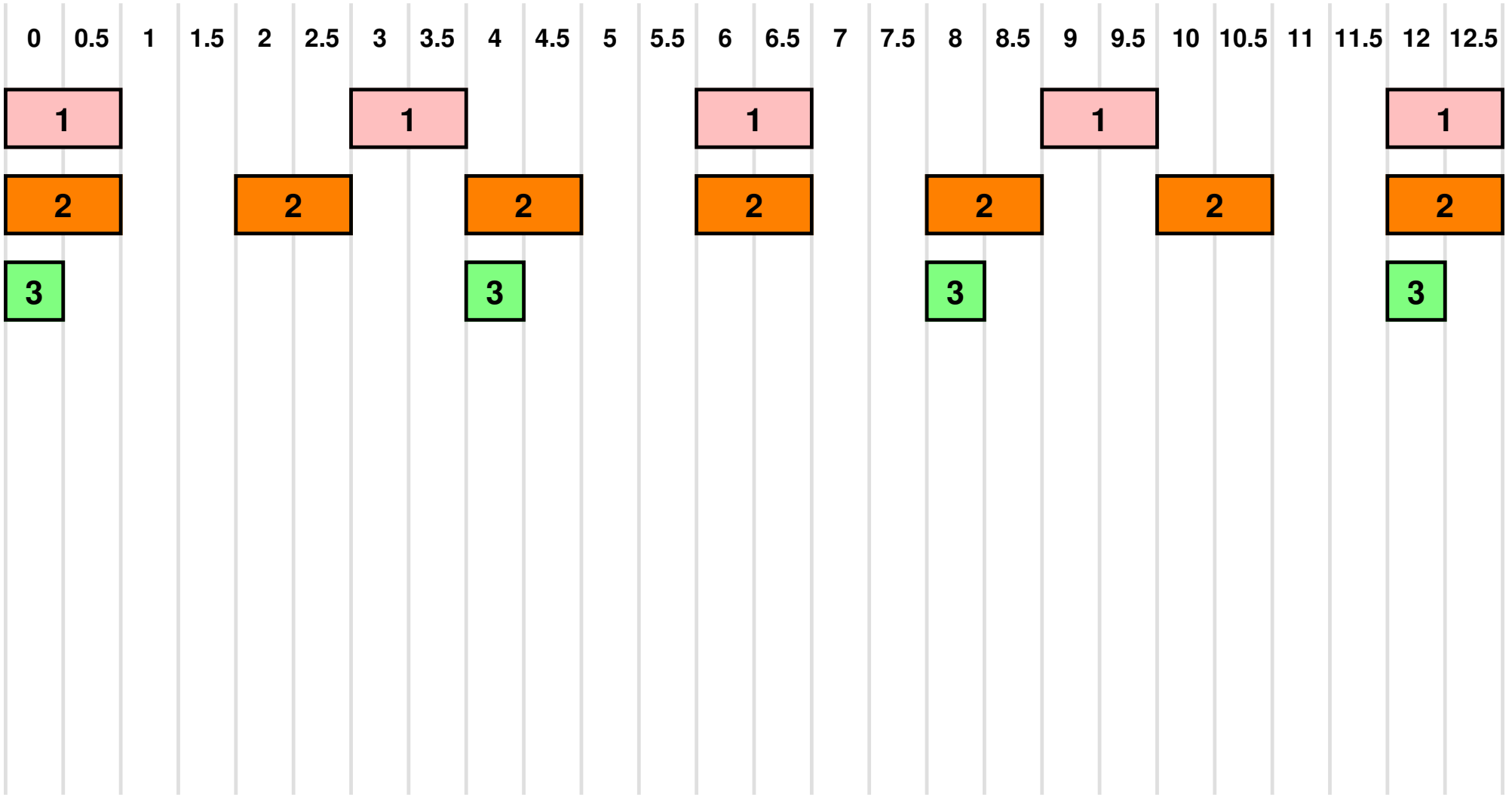
Phase Problems



- if jobs do not start in-phase, rate-monotonic scheduling still may work



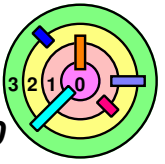
Phase Problems



see "extra slides" at the end

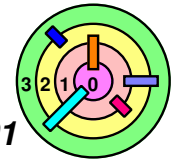
5.3 Scheduling

- Goals
- Scheduling Algorithms
- *Implementation Issues*
- Case Studies



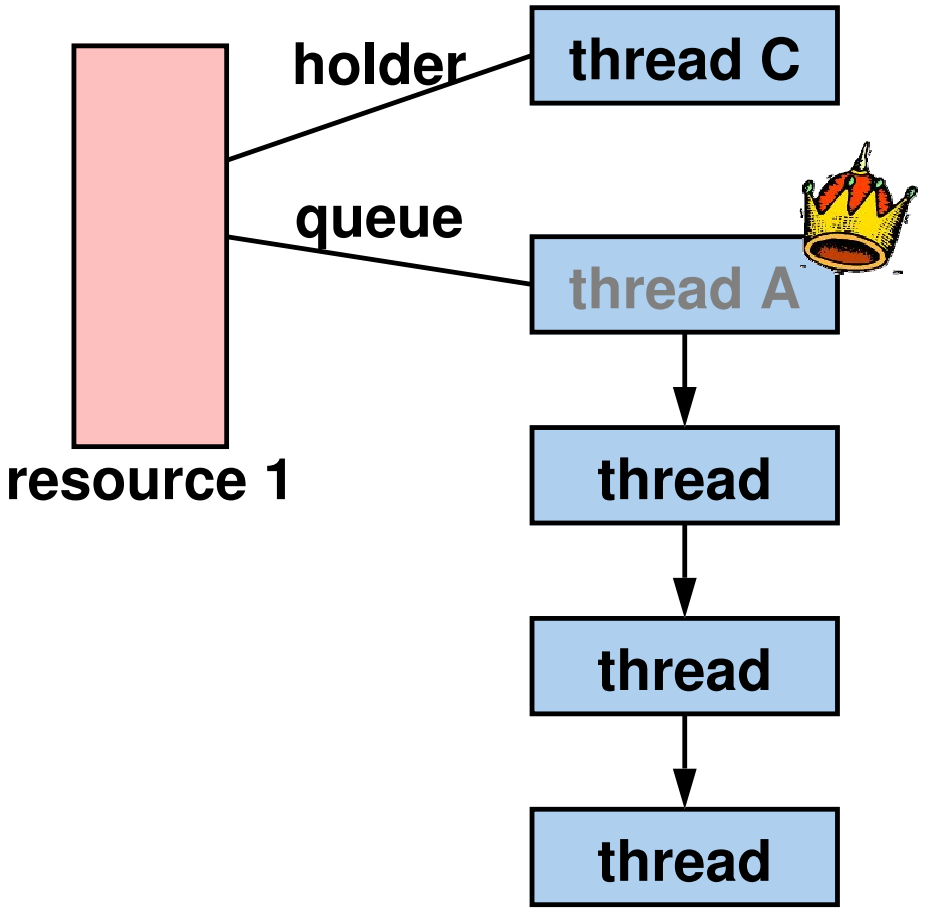
Priority Problem

- High-priority thread A blocks on mutex 1
- Low-priority thread C holds mutex 1
- Thread C cannot run because medium-priority thread B is running
- A is effectively waiting at C's priority
  - *priority inversion*



Priority Inheritance

- While A is waiting for resource held by C, it gives C its priority



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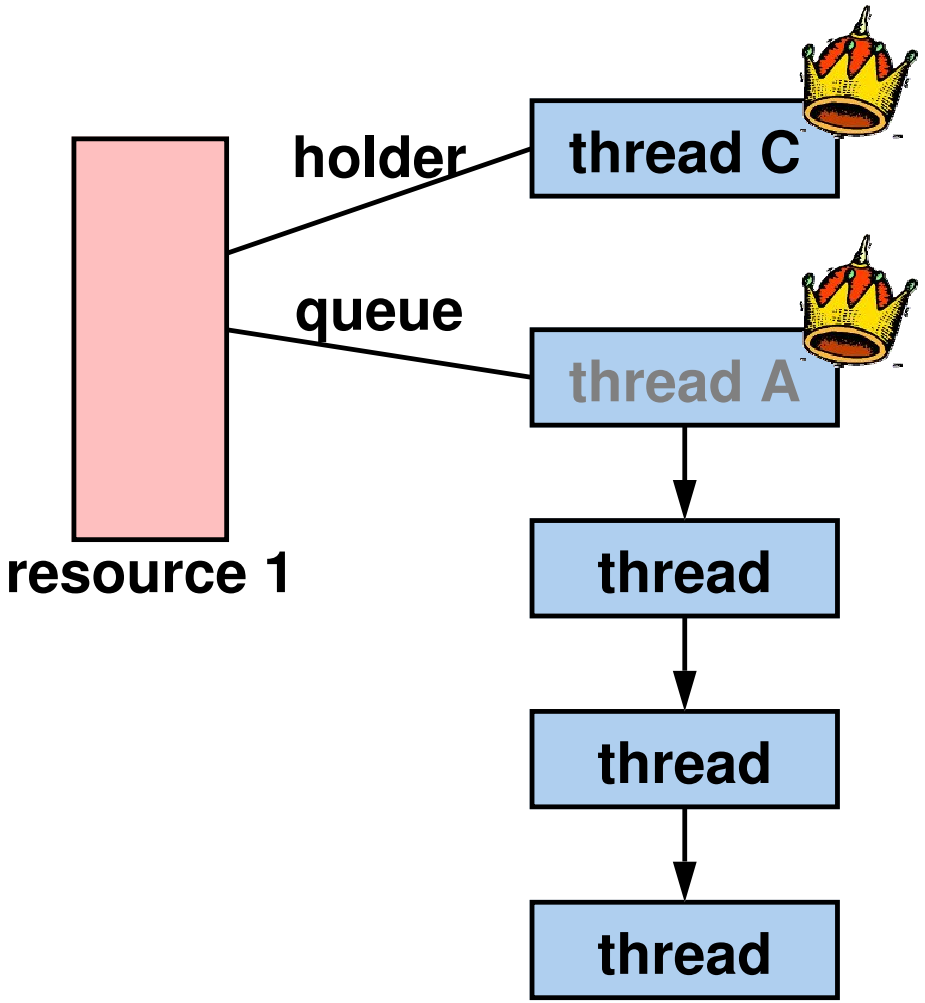
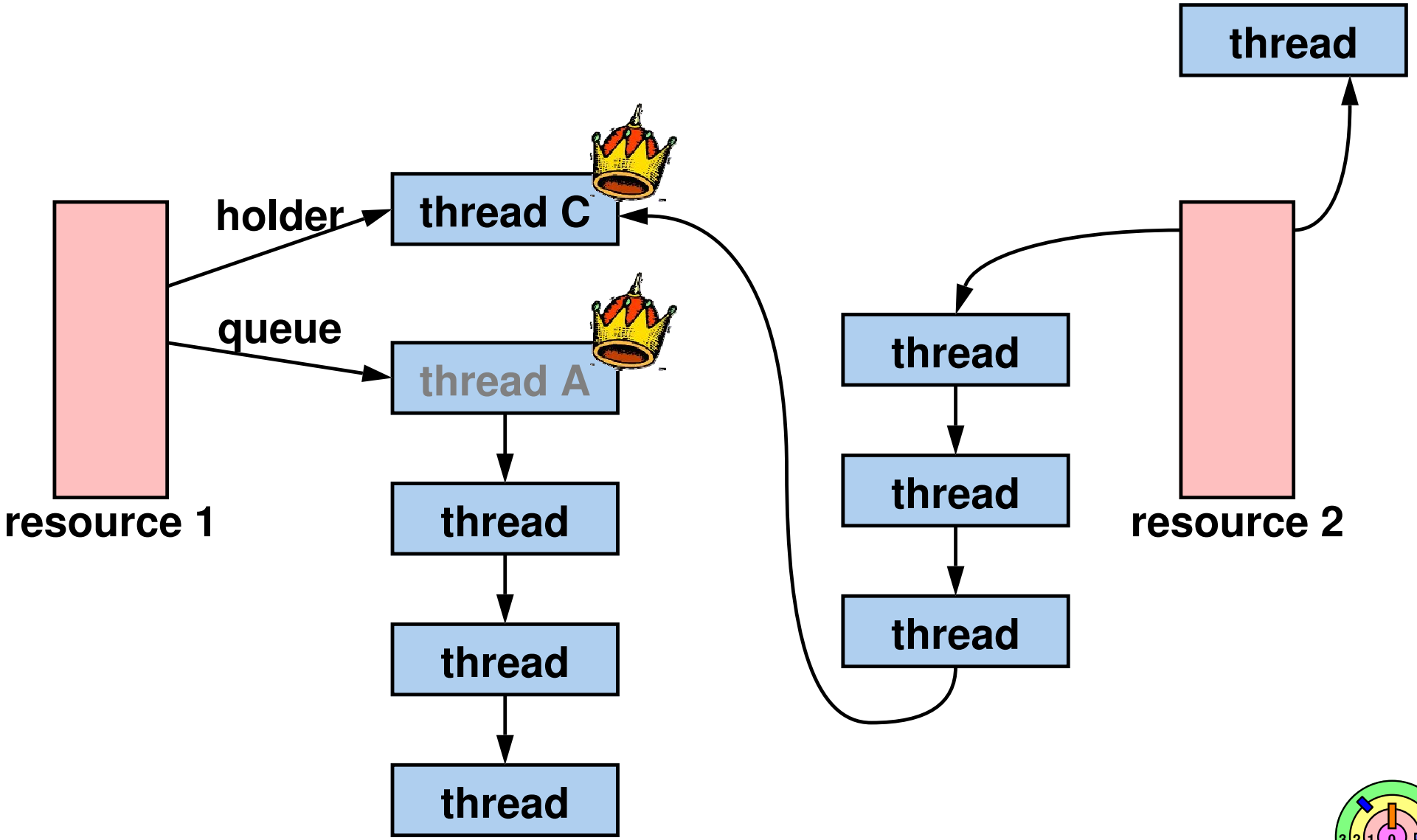


Cacading Inheritance



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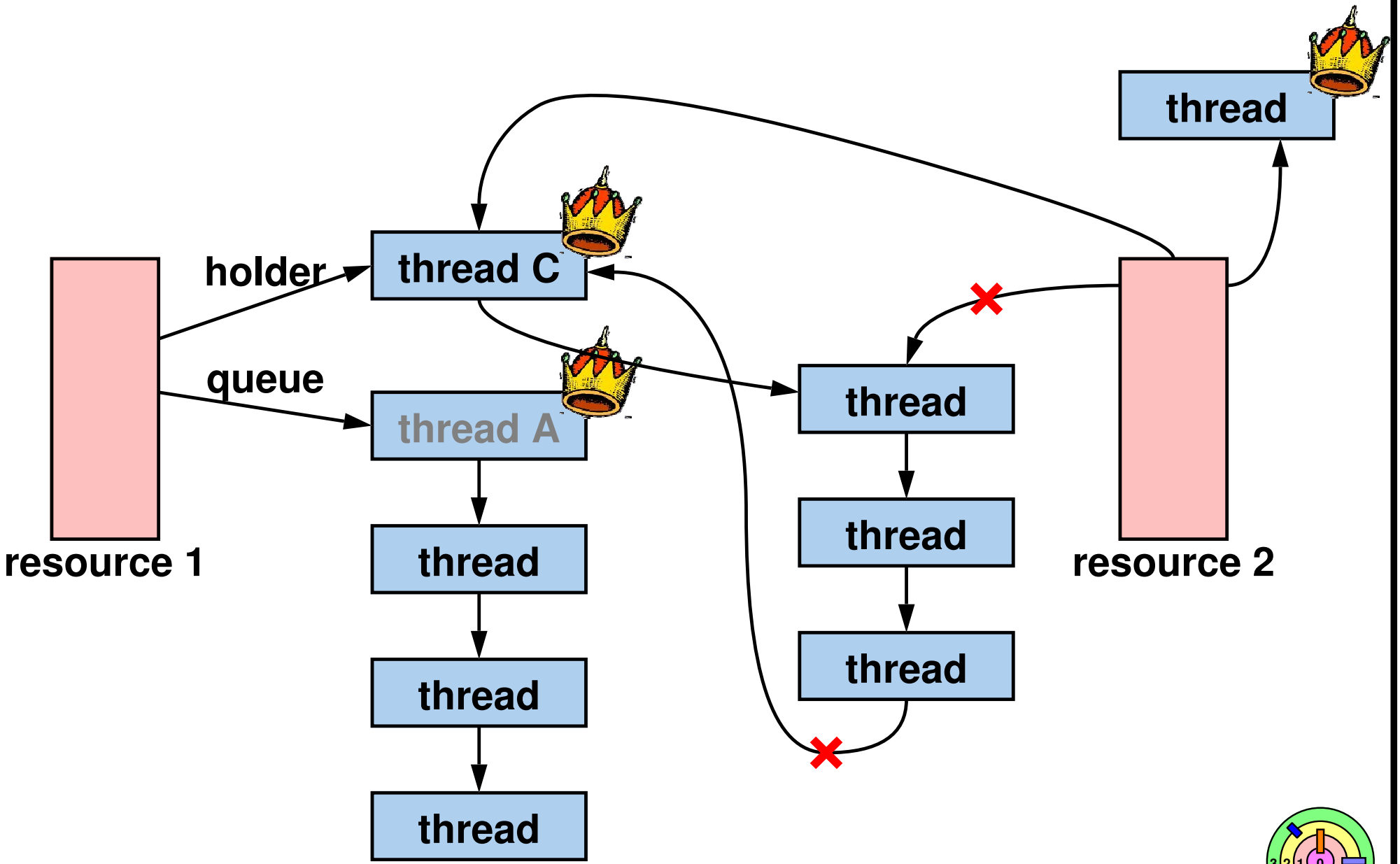
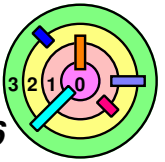


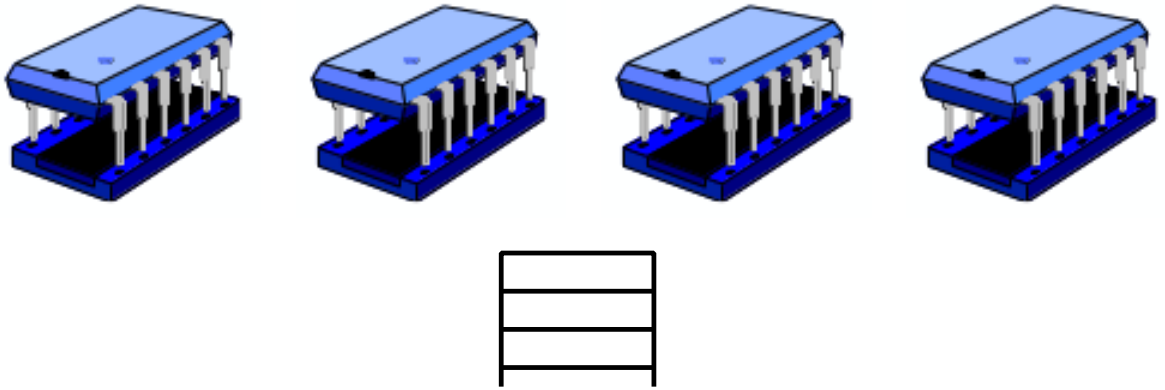
Utilizing Multiple Processors

- Dedicate processors to important threads?
- Restrict interrupt handling to certain processors?
- Windows:
  - processor affinity masks
- Solaris:
  - processor sets

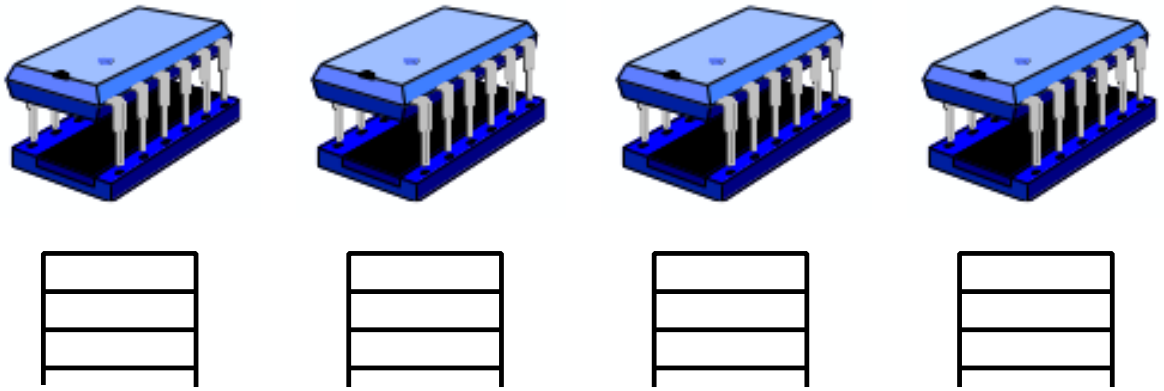


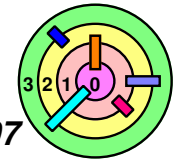
Cache Affinity

- After a thread has run on a particular processor, next time it runs, it would be cheaper to run it on the same processor
  - *cache affinity*



- This means that if you use a shared run queue for multiple processors, you will not be able to take advantage of cache affinity
  - therefore, you should use one run queue per processor





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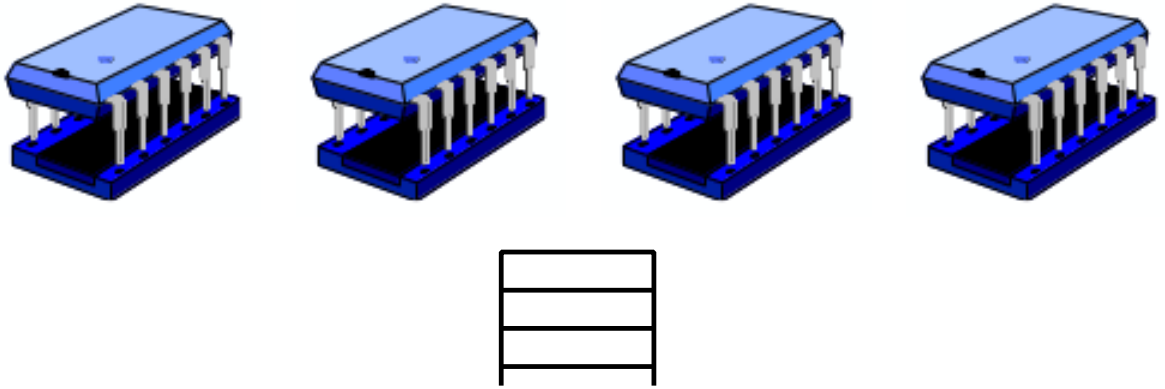
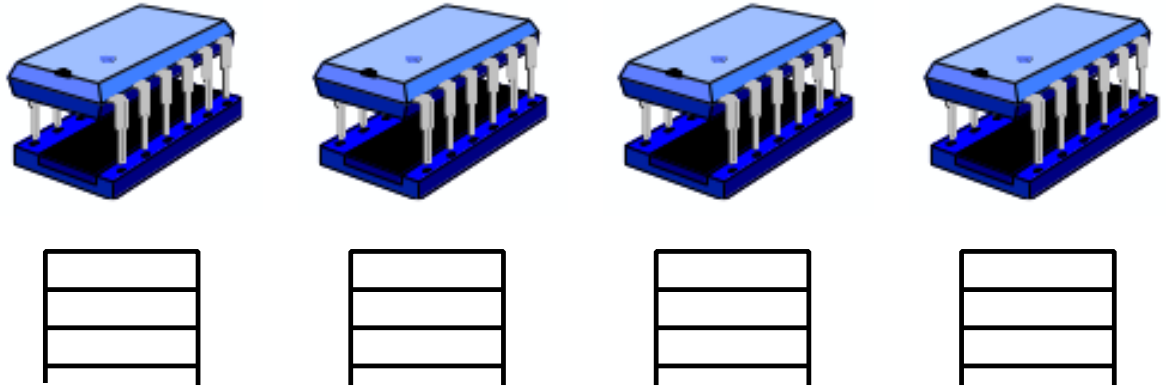
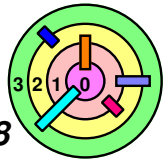
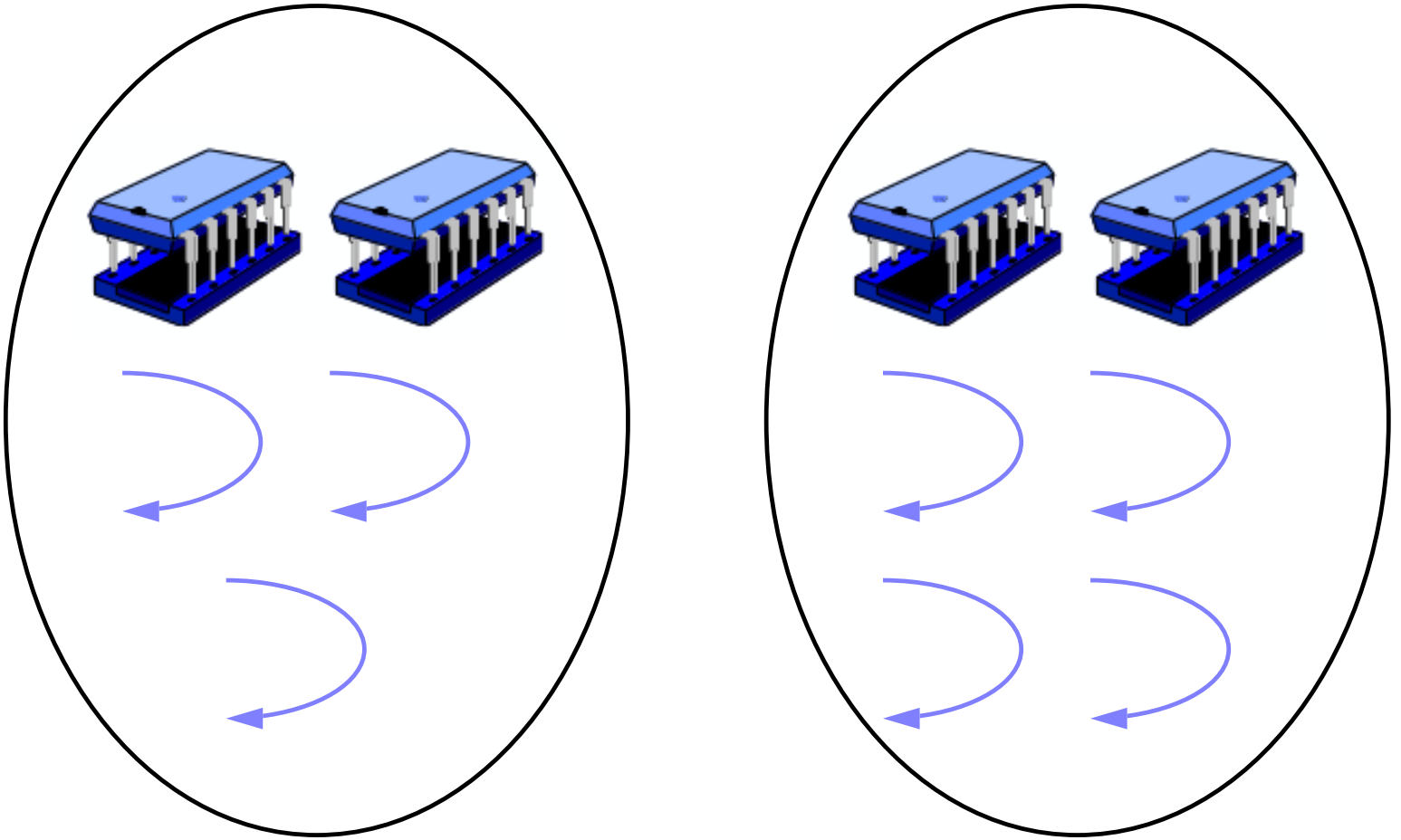


- This means that if you use a shared run queue for multiple processors, you will not be able to take advantage of cache affinity
  - therefore, you should use one run queue per processor
  - scheduler may do *load balancing* occasionally

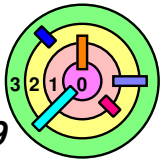




Solaris: Processor Sets

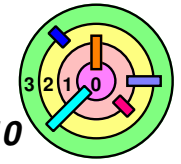


- Somewhere between the two extremes



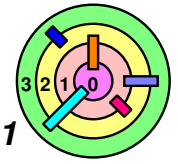
5.3 Scheduling

- Goals
- Scheduling Algorithms
- Implementation Issues
- *Case Studies*



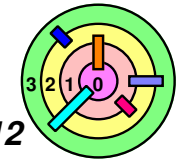
Linux Scheduling

- Policies mandated by POSIX
  - SCHED_FIFO (highest)
    - "real time"
    - *infinite time quantum*
  - SCHED_RR
    - "real time"
    - *adjustable time quantum*
  - SCHED_OTHER
    - "normal" scheduler
    - parameterized allocation of processor time



Linux Scheduler Evolution

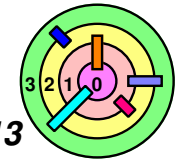
- Old scheduler
  - very simple
  - poor scaling
- O(1) scheduler
  - introduced in 2.5
  - less simple
  - better scaling
- Completely fair scheduler *(CFS)*
  - even better
  - simpler in concept
  - much less so in implementation
  - based on *stride* scheduling



Old Scheduler

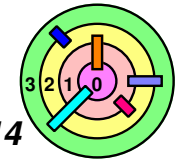
- Four per-process scheduling variables
  - *policy:* which one
  - *rt_priority:* real-time priority
    - 0 for SCHED_OTHER
    - 1 - 99 for others
  - *priority:* time-slice parameter ("nice" value)
  - *counter:* records processor consumption

- see "extra slides" at the end



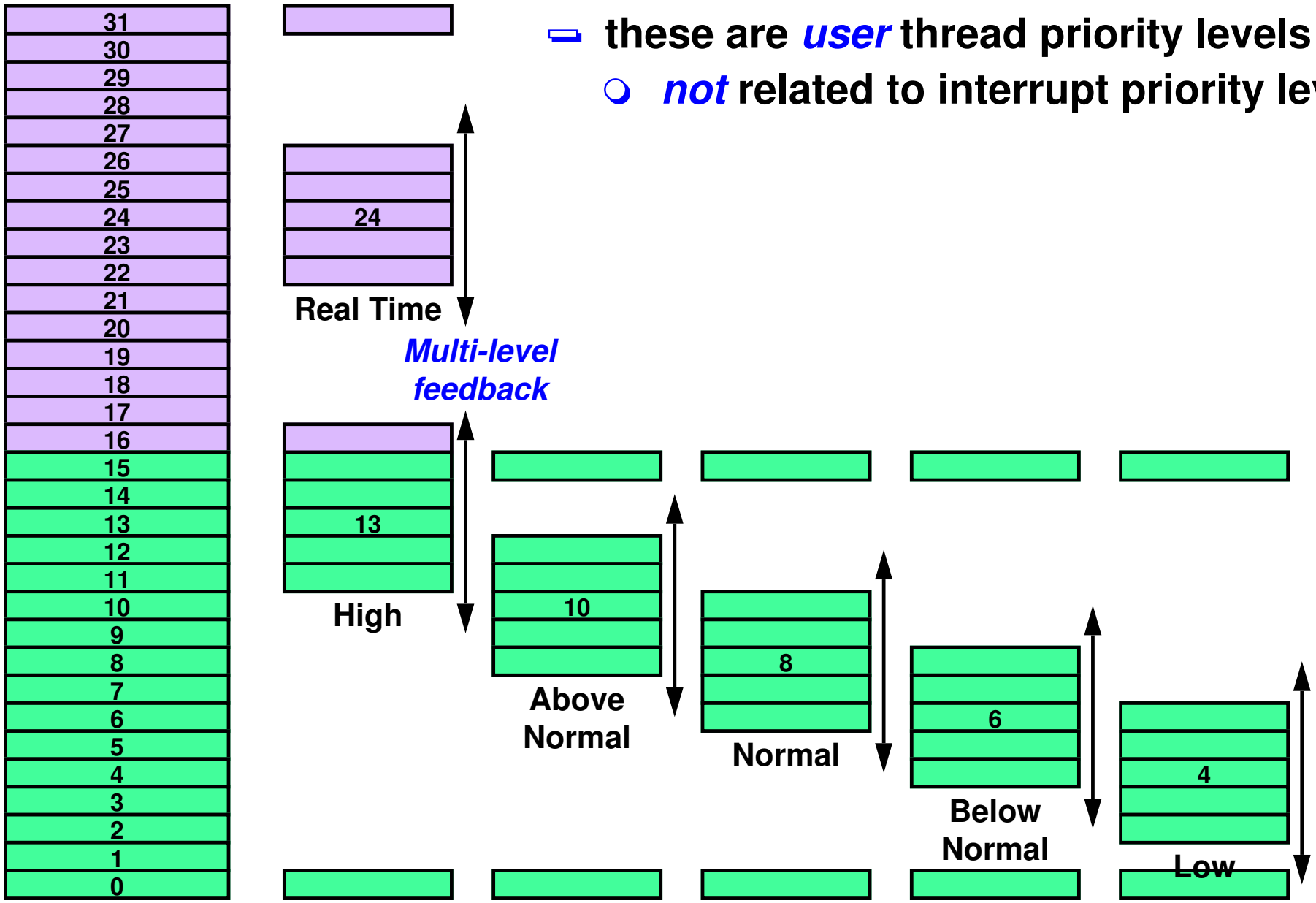
Scheduling in Windows

- Handling "normal" interactive and compute-bound threads
- Real-time threads
- Multiple processors

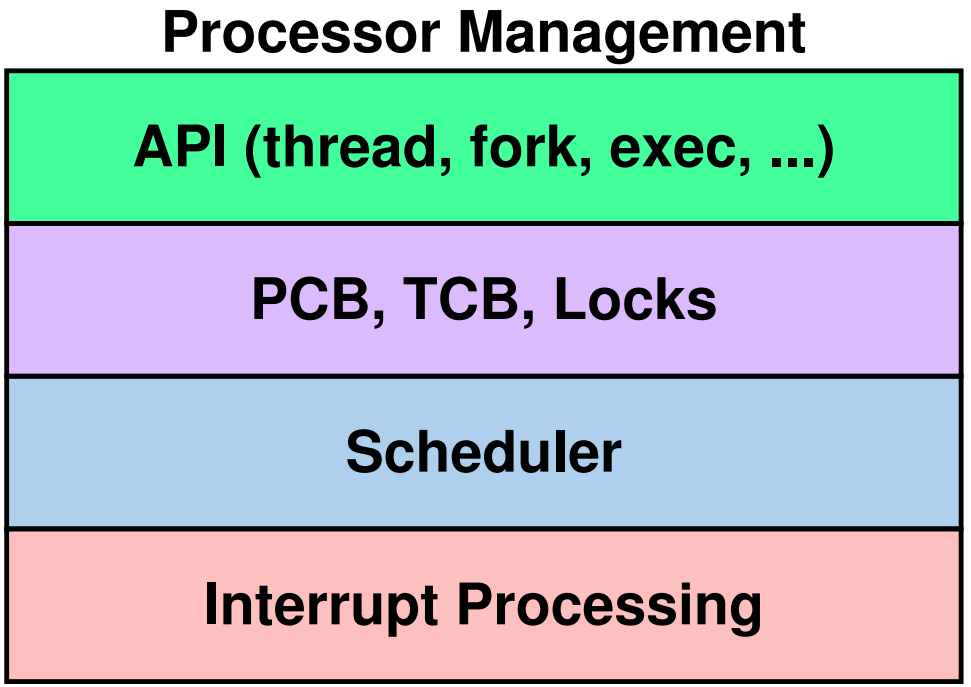


Windows Priority Classes and Levels

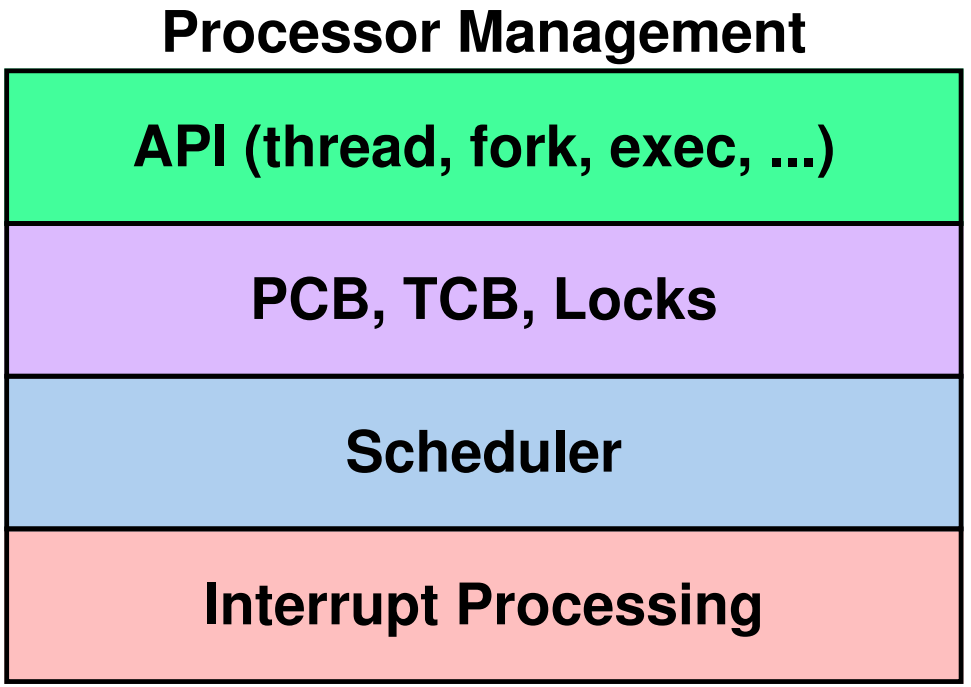
- these are *user* thread priority levels
  - *not* related to interrupt priority levels



Processor Management Summary

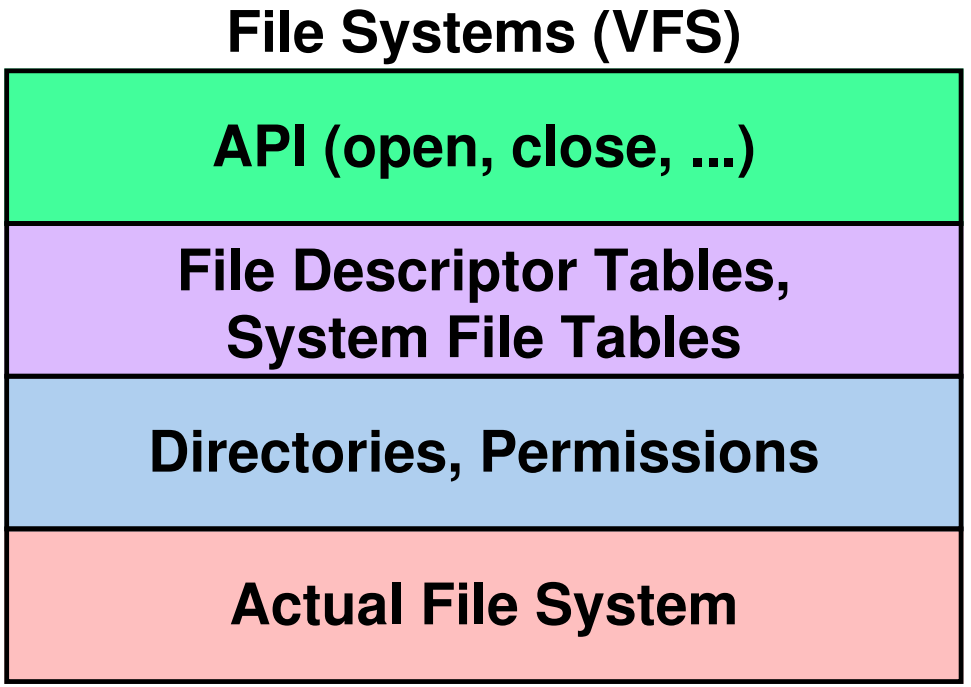


Processor Management Summary

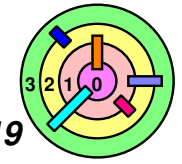


Try visualizing what happens when you do "ls" in the console

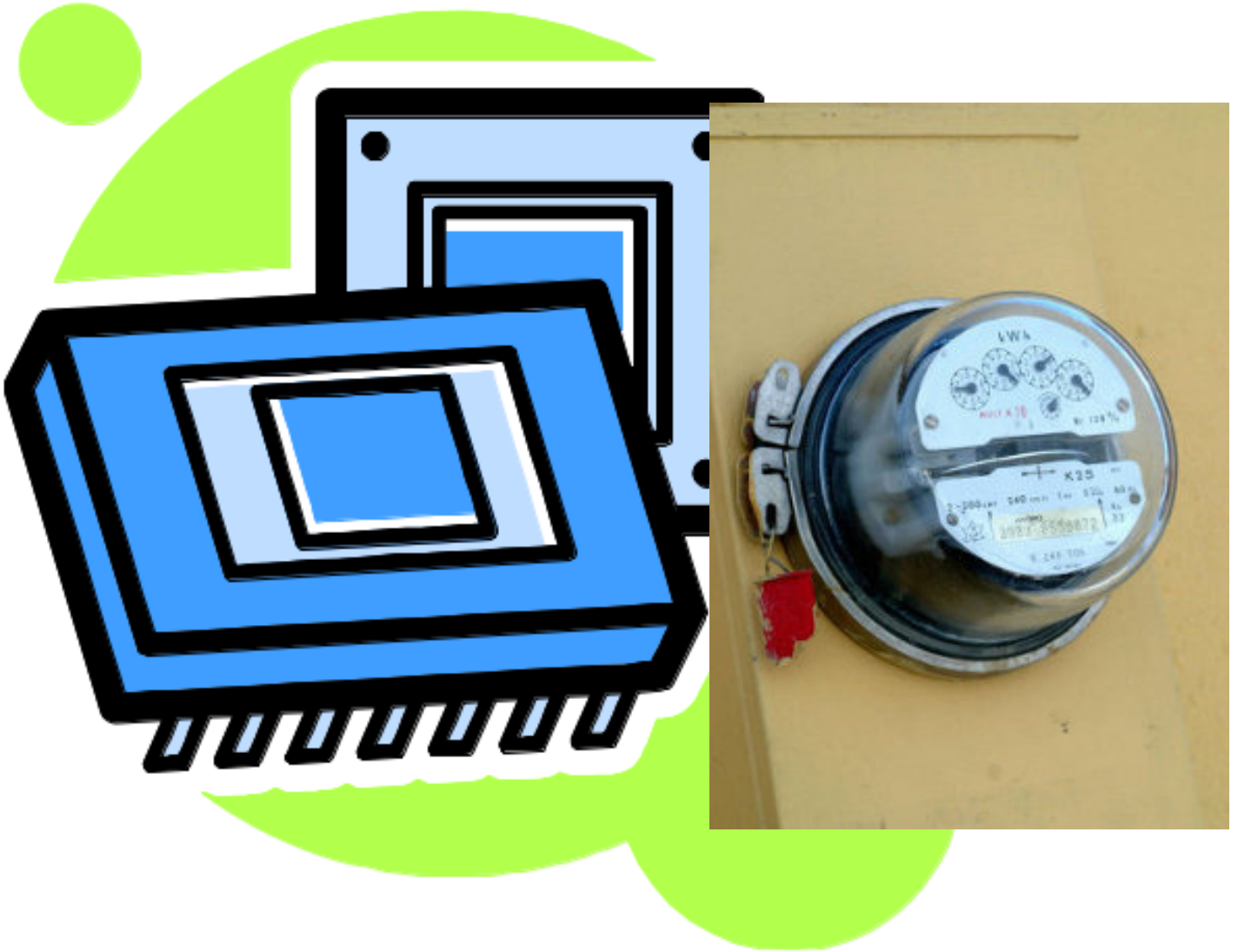
File Systems Overview



Extra Slides



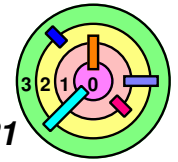
Metered Processors



- see "extra slides" at the end

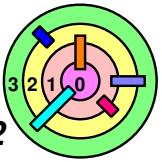
Algorithm

- Each thread has a meter, which runs only when the thread is running on the processor
- At every clock tick
  - give processor to thread that's had the least processor time as shown on its meter
  - in case of tie, thread with lowest ID wins

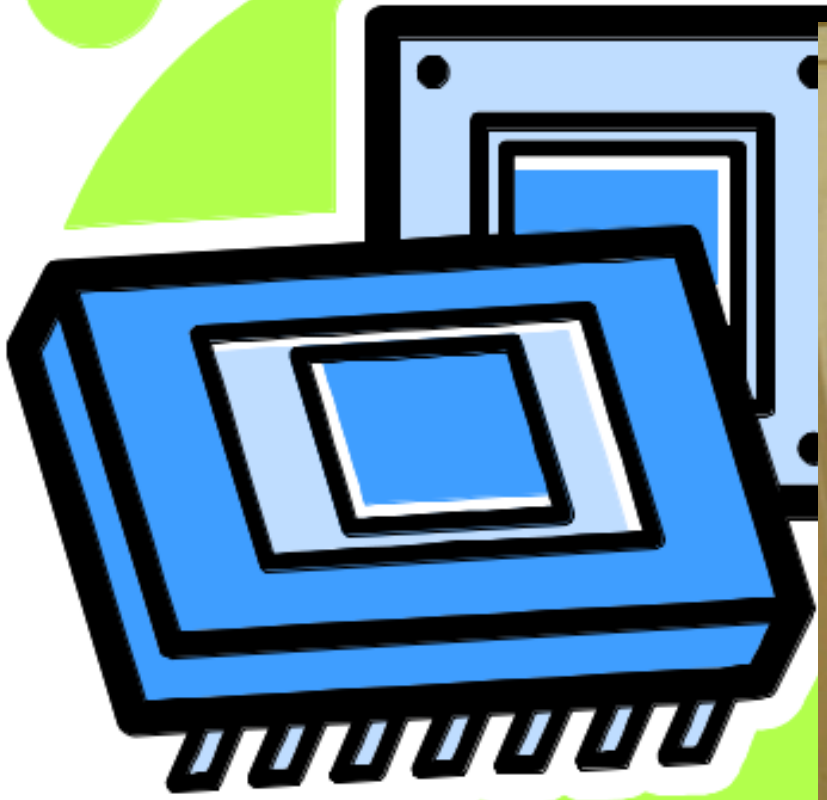


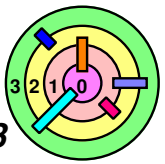
Algorithm

- Some threads may be more important than others
- What if new threads enter system?
- What if threads block for I/O and synchronization?



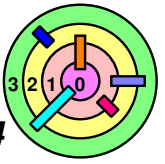
Metered Processors (Mafia Variation)





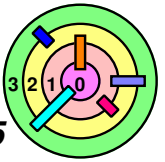
Details ...

- Each thread pays a bribe
  - the greater the bribe, the slower the meter runs
  - to simplify bribing, you buy "tickets"
  - one ticket is required to get a fair meter
  - two tickets get a meter running at half speed
  - three tickets get a meter running at 1/3 speed
  - etc.

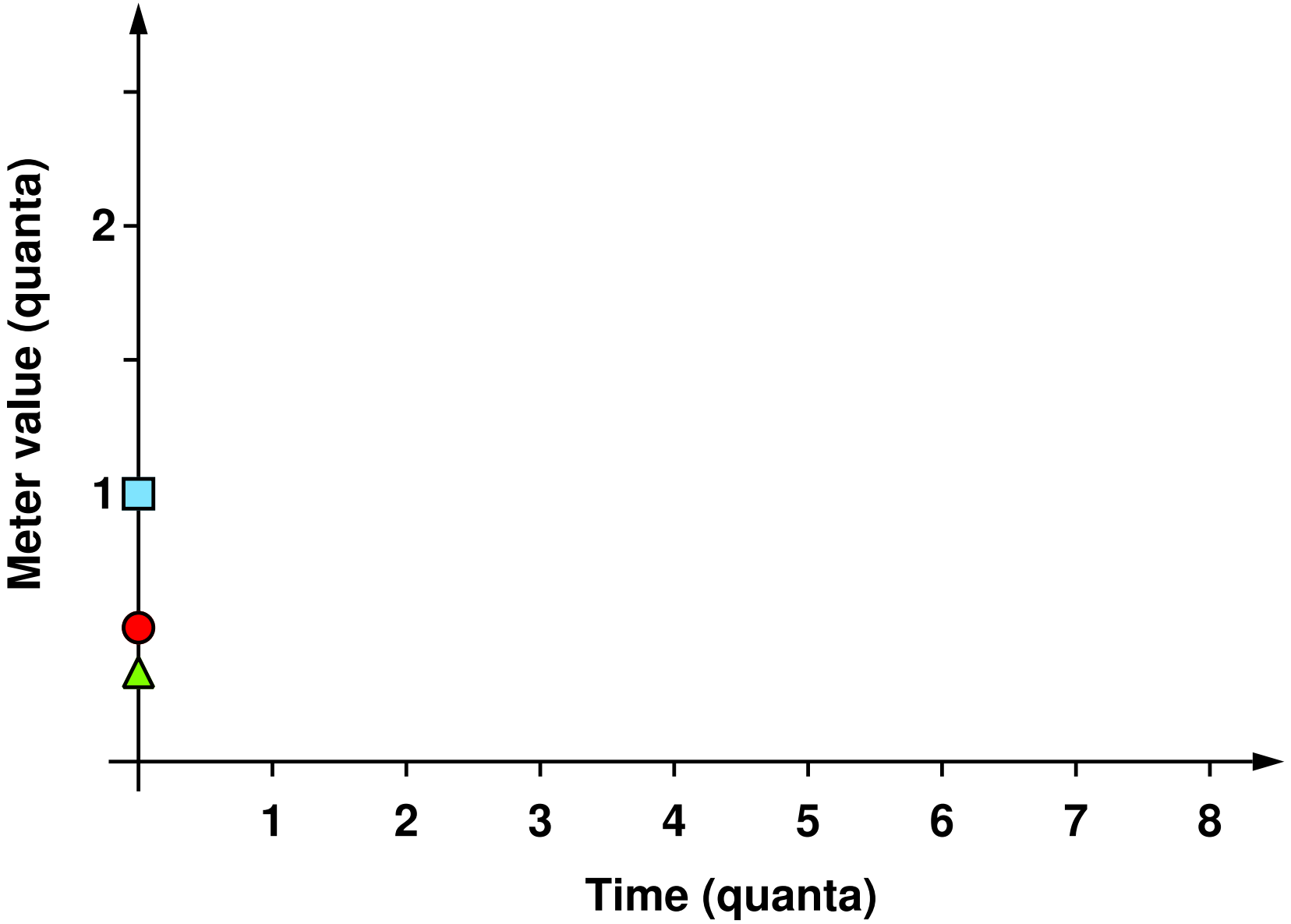


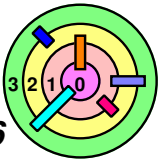
New Algorithm

- Each thread has a (possibly crooked) meter, which runs only when the thread is running on the processor
- At every clock tick
  - give processor to thread that's had the least processor time as shown on its meter
  - in case of tie, thread with lowest ID wins

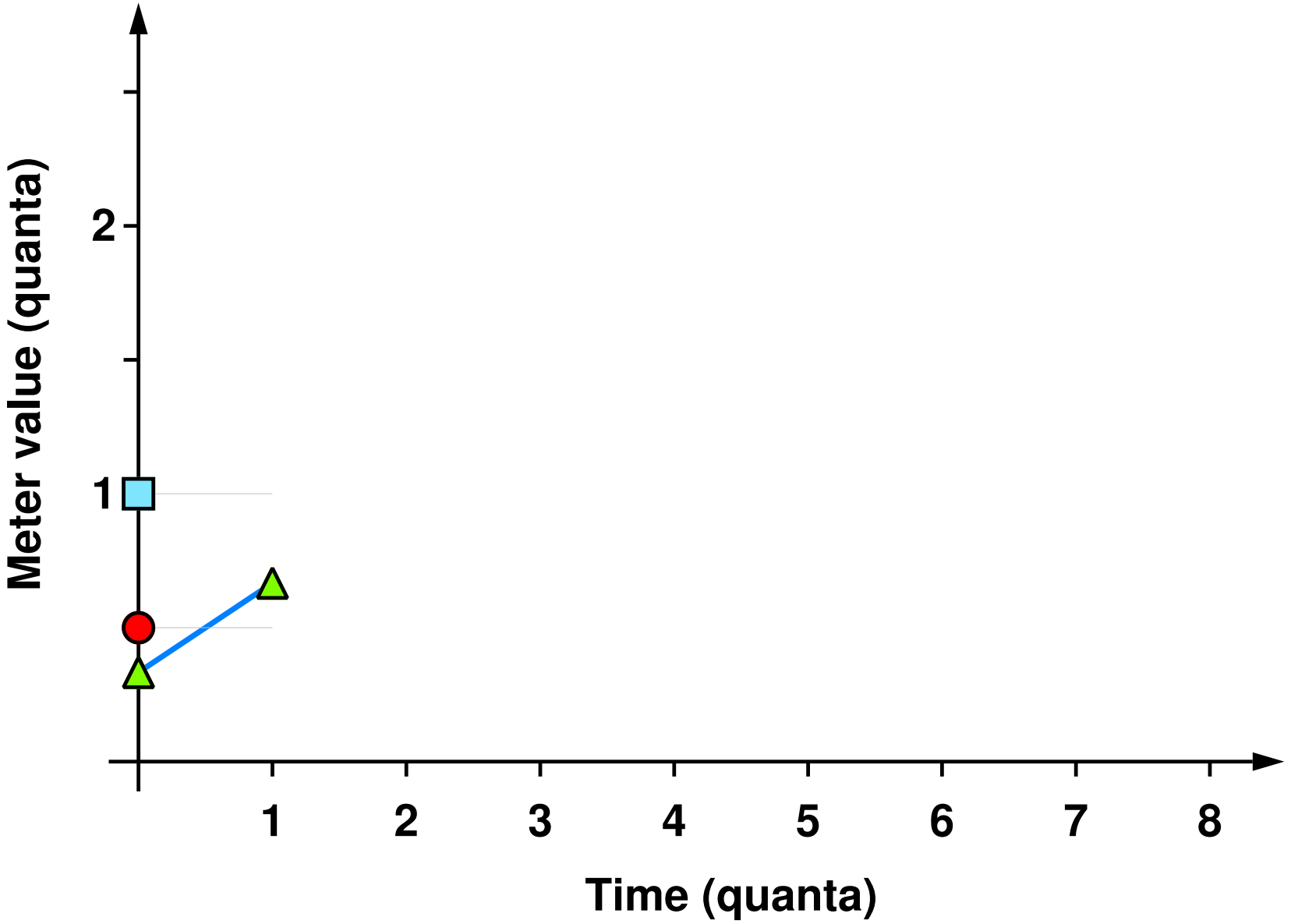


Example

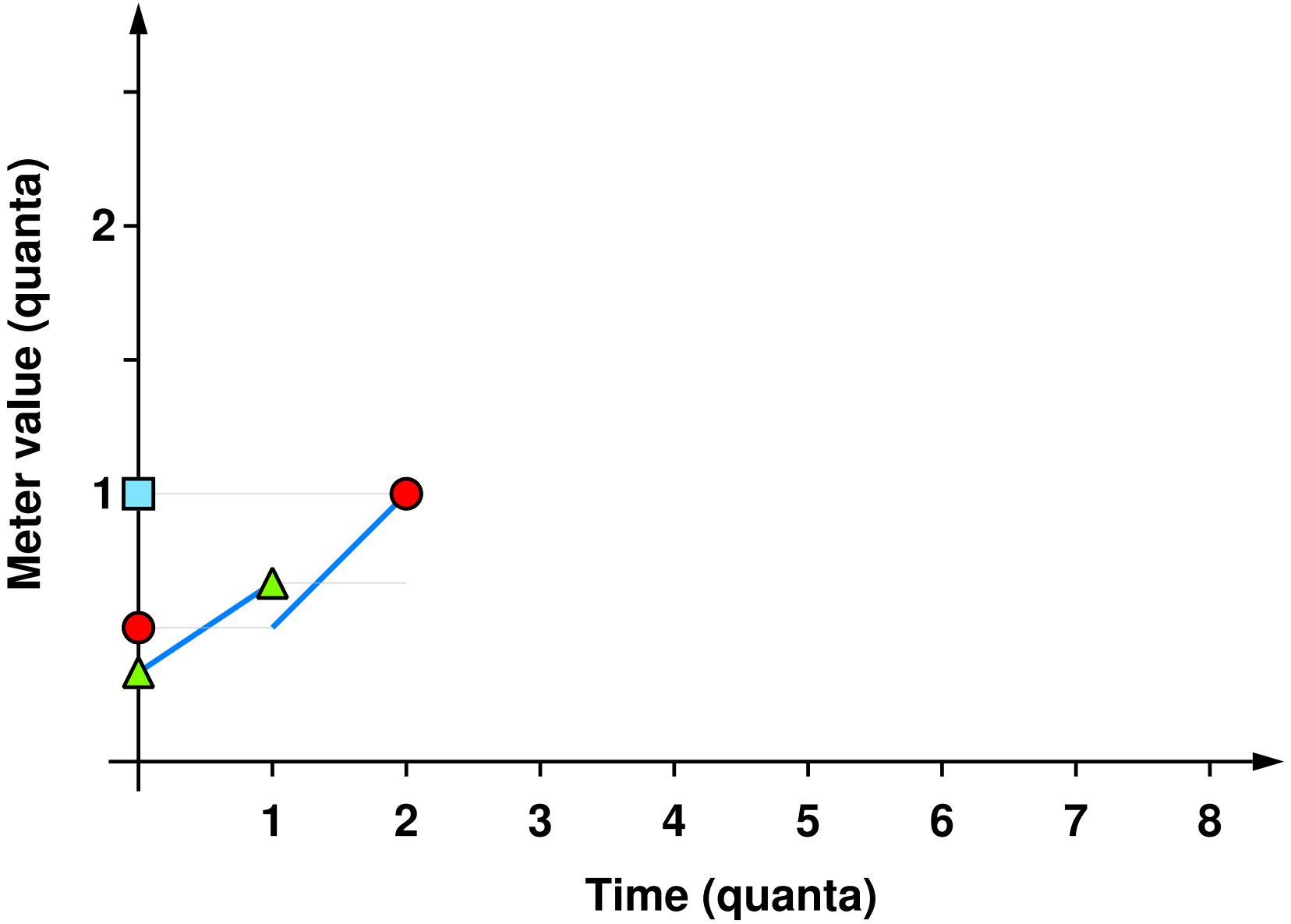




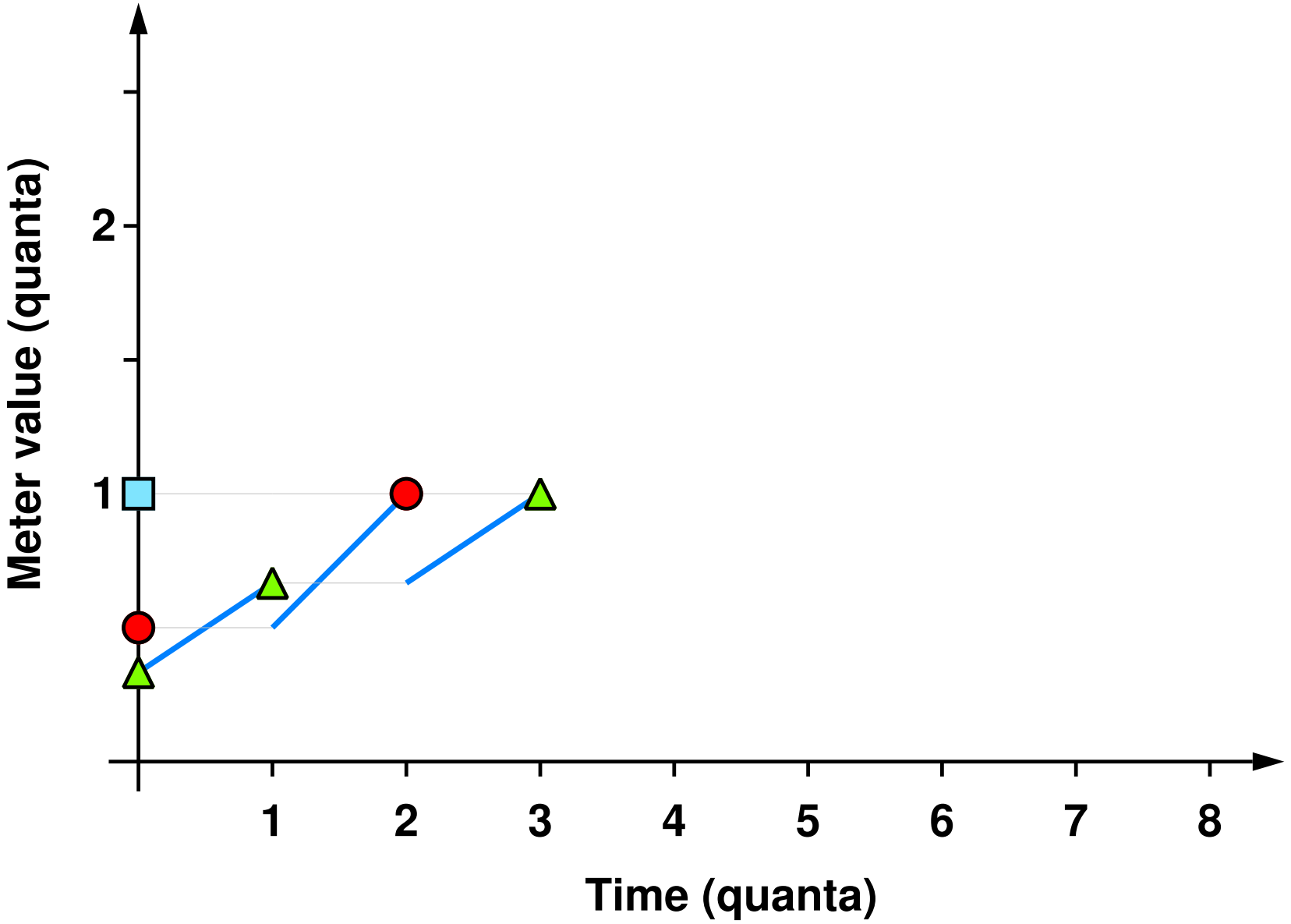
Example



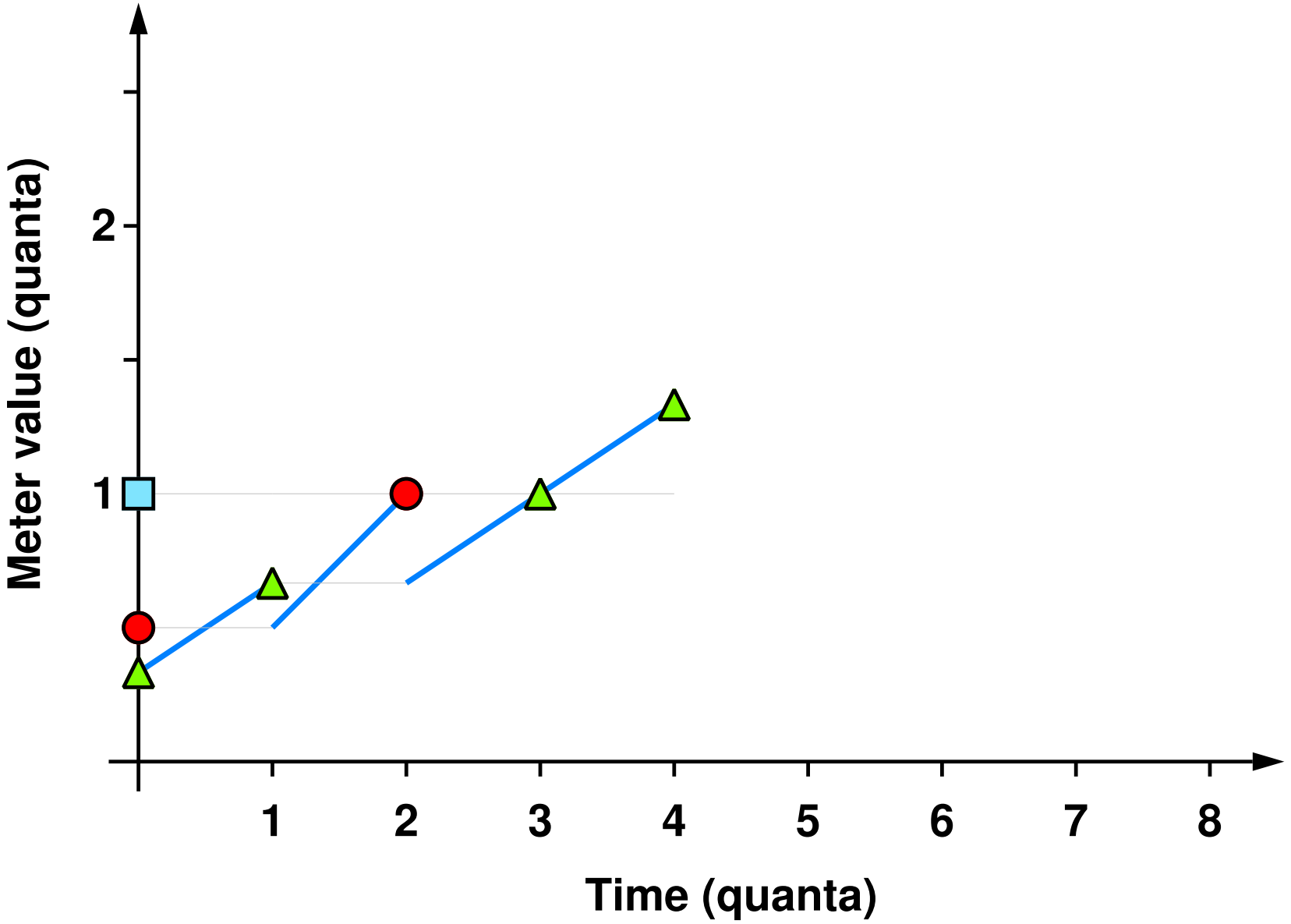
Example



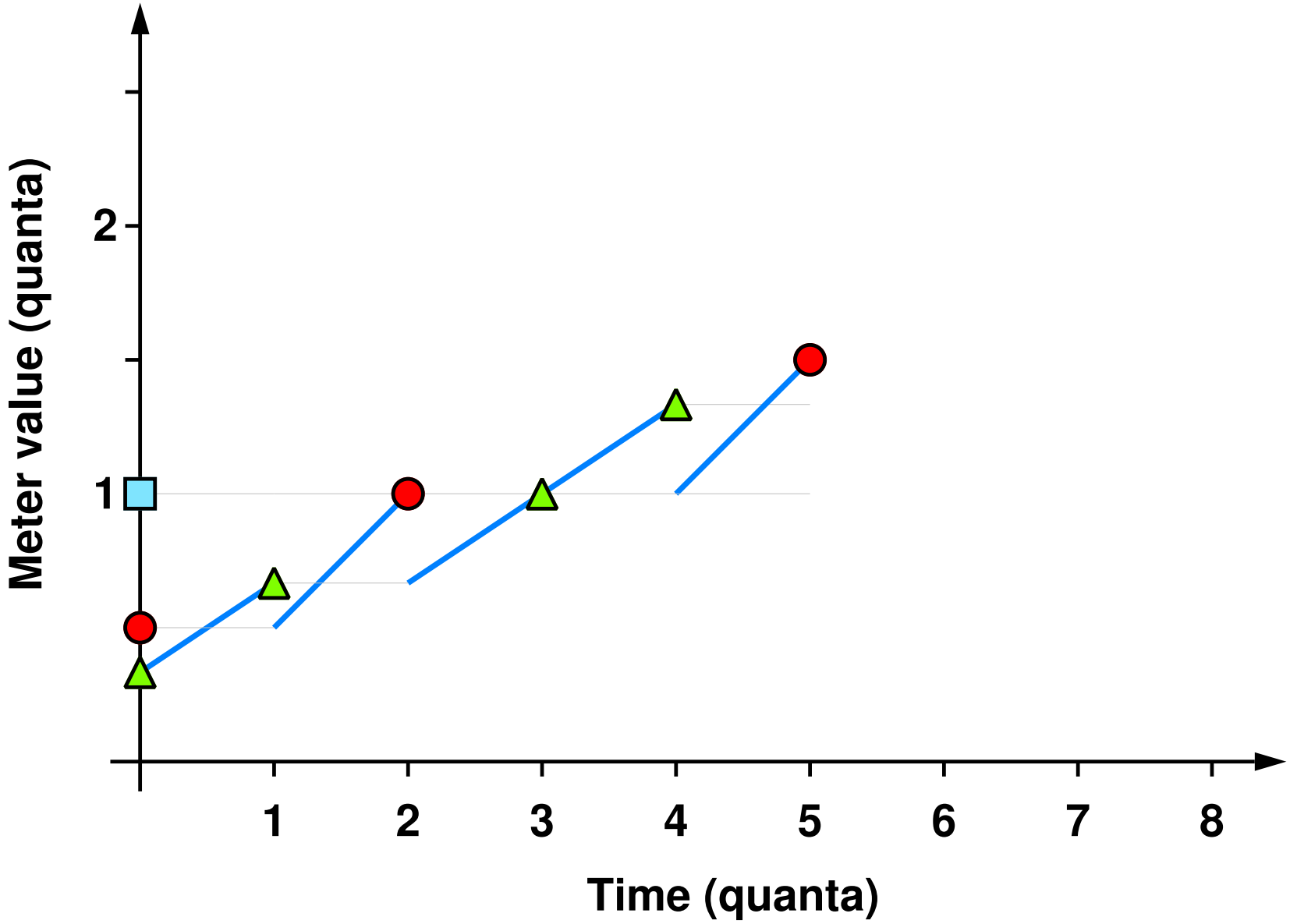
Example



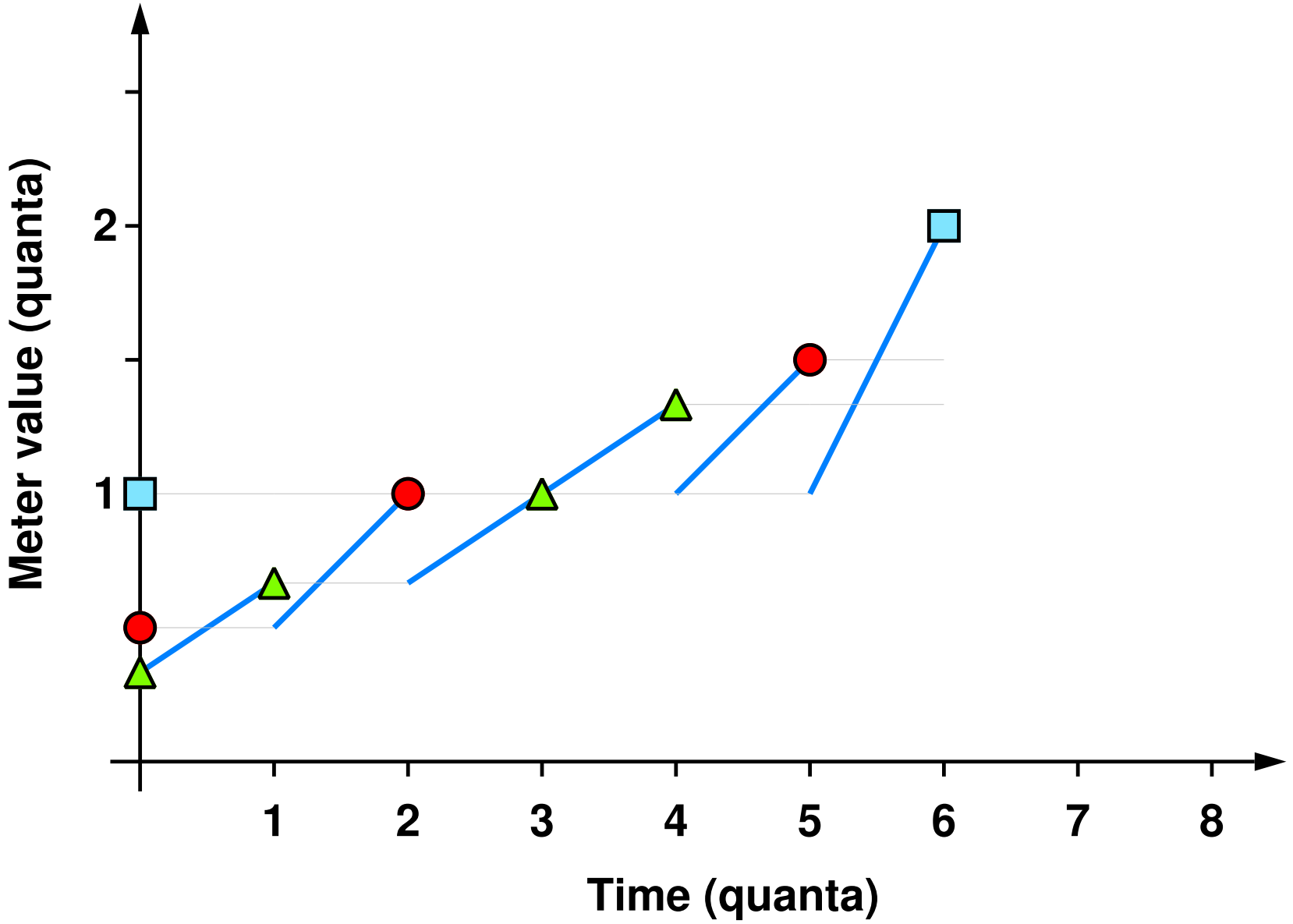
Example



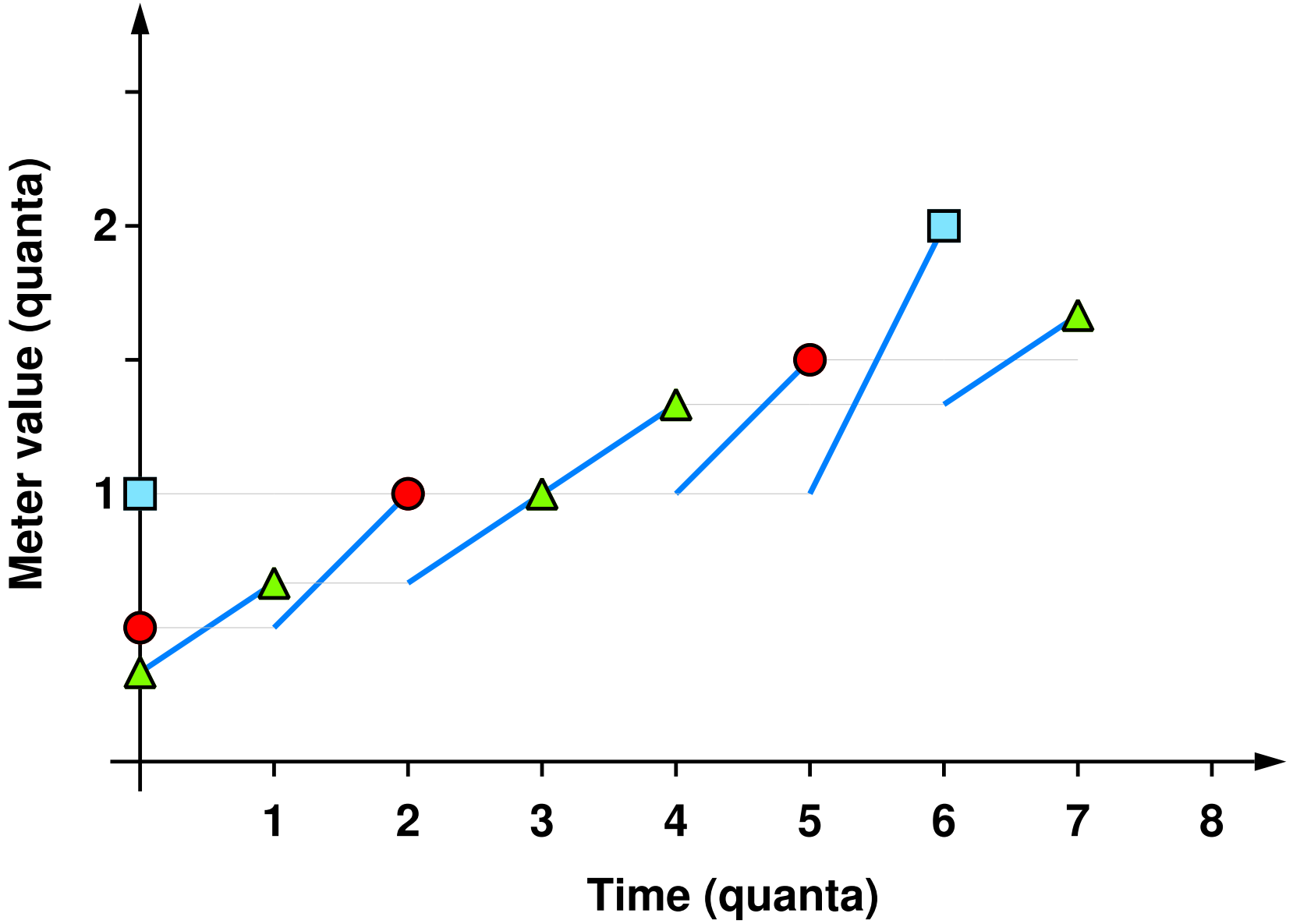
Example



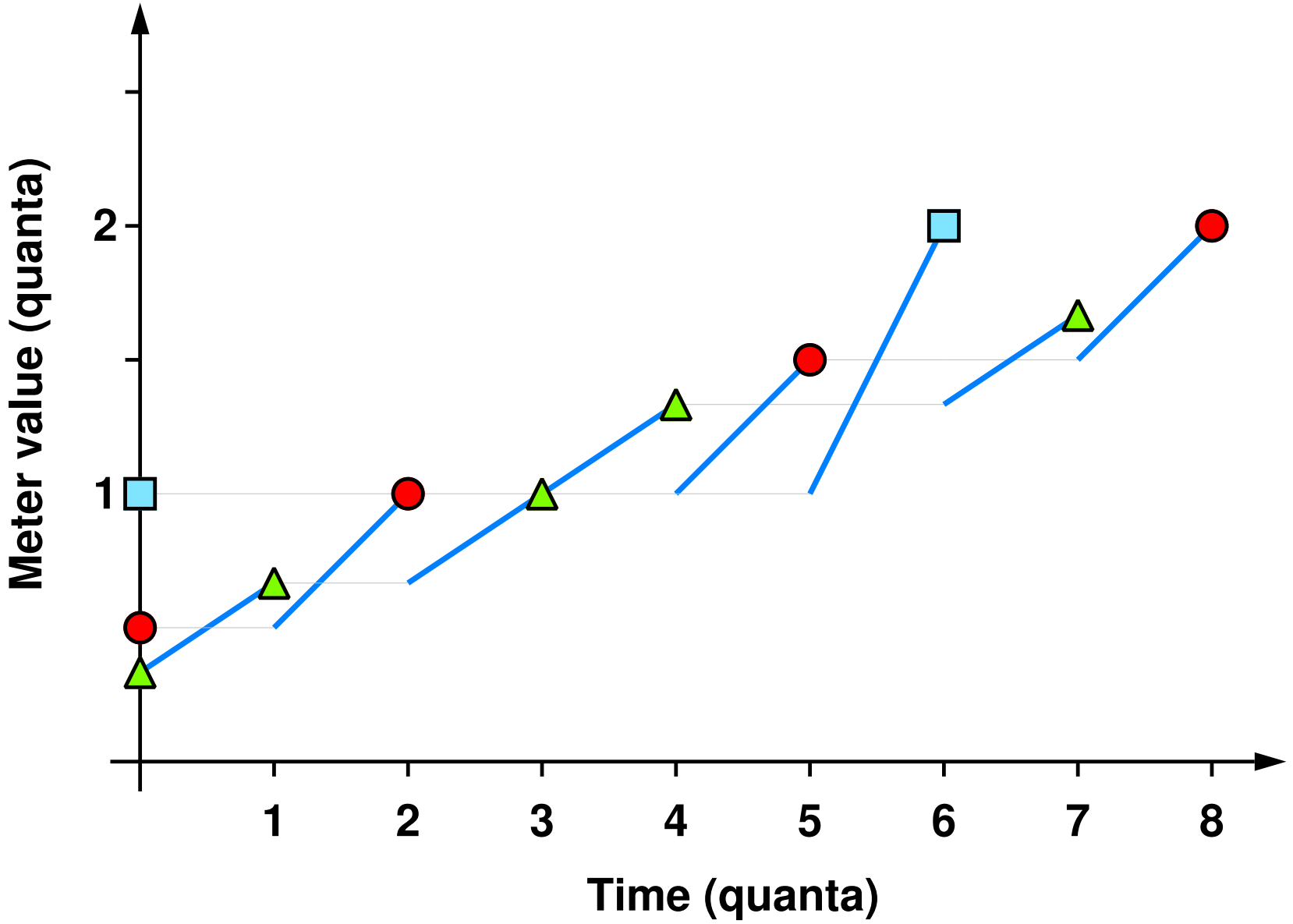
Example



Example

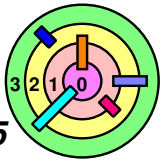


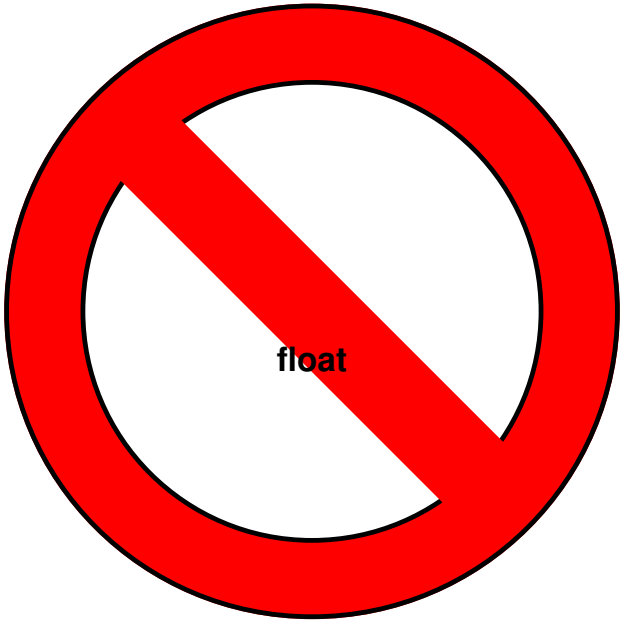
Example

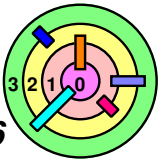


More Details

```
typedef struct {
  float bribe, meter_rate, metered_time;
} thread_t;

void thread_init(thread_t *t, float bribe) {
  if (bribe < 1)
    abort();
  t->bribe = bribe;
  t->meter_rate = t->metered_time = 1.0/bribe;
  InsertQueue(t);
}
```

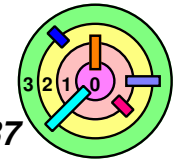






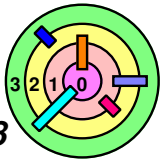
More Details (revised)

```
typedef struct {
  long long bribe, meter_rate, metered_time;
} thread_t;

const long long BigInt = 2^20;

void thread_init(thread_t *t, long bribe) {
  if (bribe < 1)
    abort();
  t->bribe = bribe;
  t->meter_rate = t->metered_time = BigInt/bribe;
}
```



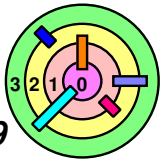
More Details (continued)

```
void OnClockTick() {
  thread_t *NextThread;

  CurrentThread->metered_time +=
      CurrentThread->meter_rate;
  InsertQueue(CurrentThread);
  NextThread = PullSmallestThreadFromQueue();
  if (NextThread != CurrentThread)
    SwitchTo(NextThread);
}
```



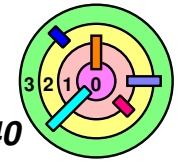
Handling New Threads

- It's time to get an accountant ...
  - keep track of total bribes
  - TotalBribe = total number of tickets in use
  - keep track of actual (normalized) processor time: `TotalTime`
  - measured by a "fixed" meter going at the rate of 1/TotalBribe
    - BigInt/TotalBribe when we convert from floating point
- New thread
  - pays bribe, gets meter
  - `metered_time` initialized to `TotalTime+meter_rate`



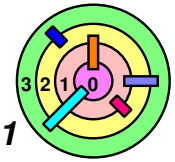
Revised Details

```
void OnClockTick() {
  thread_t *NextThread;

  TotalTime += BigInt/TotalBribe;
  CurrentThread->metered_time +=
      CurrentThread->meter_rate;
  InsertQueue(CurrentThread);
  NextThread =
      PullSmallestThreadFromQueue();
  if (NextThread != CurrentThread)
    SwitchTo(NextThread);
}
```

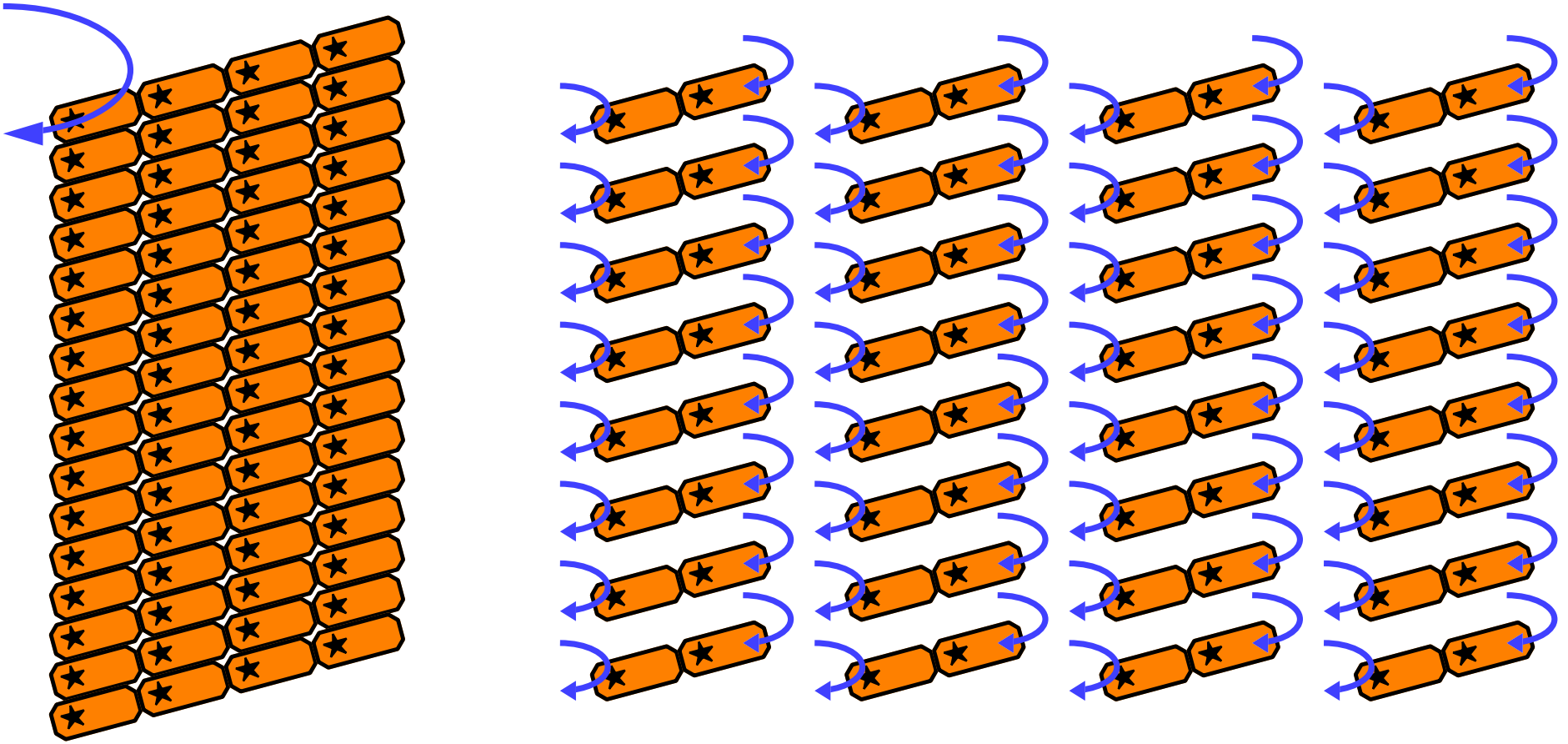


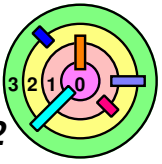
Thread Leaves, then Returns

```
void ThreadDepart(thread_t *t) {
  t->remaining_time =
       t->metered_time - TotalTime;
  // remaining_time is a new component
}

void ThreadReturn(thread_t *t) {
  t->metered_time =
       TotalTime + t->remaining_time;
}
```

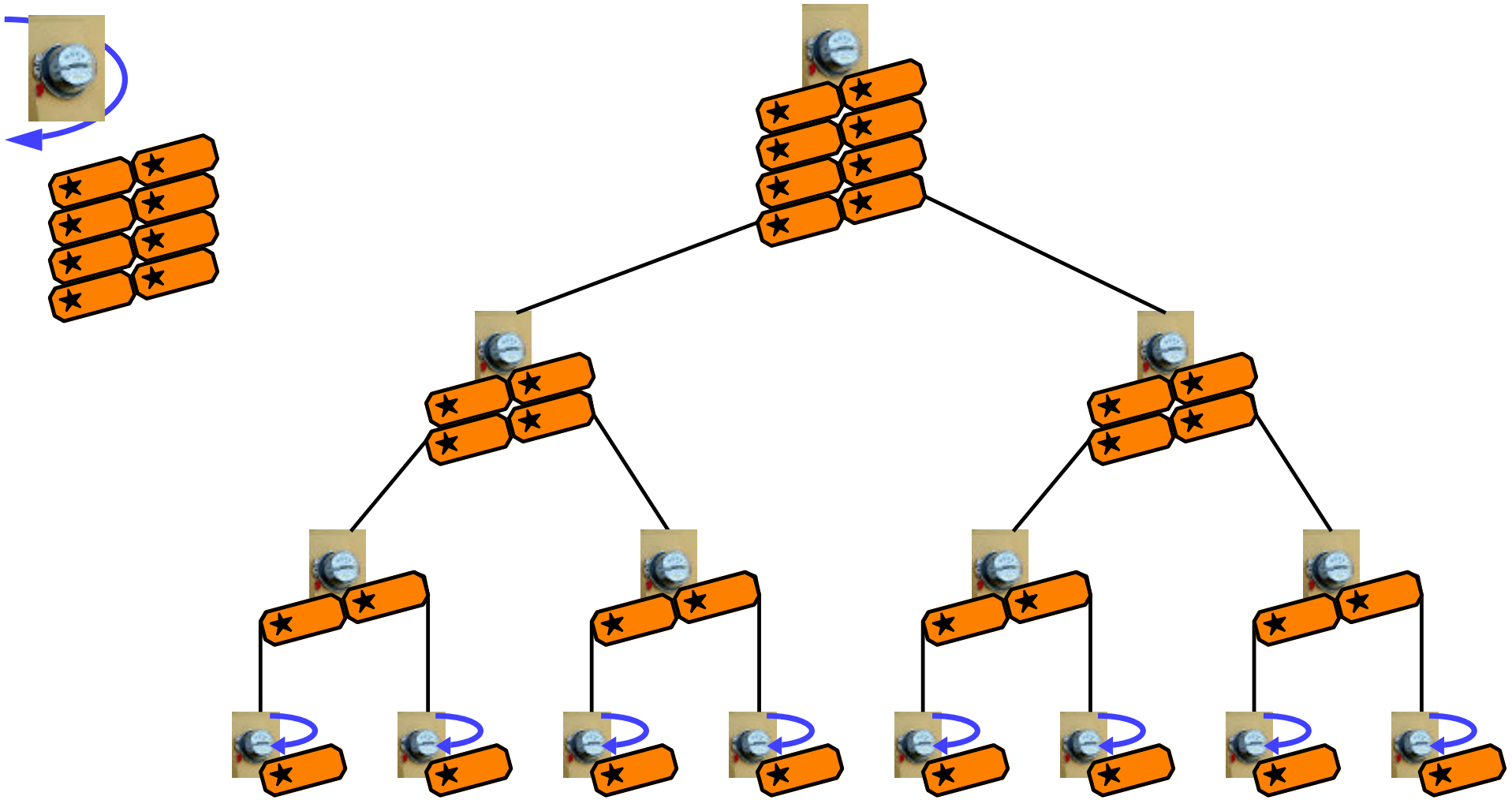


A Mismatch



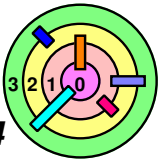


Hierarchical Stride Scheduling

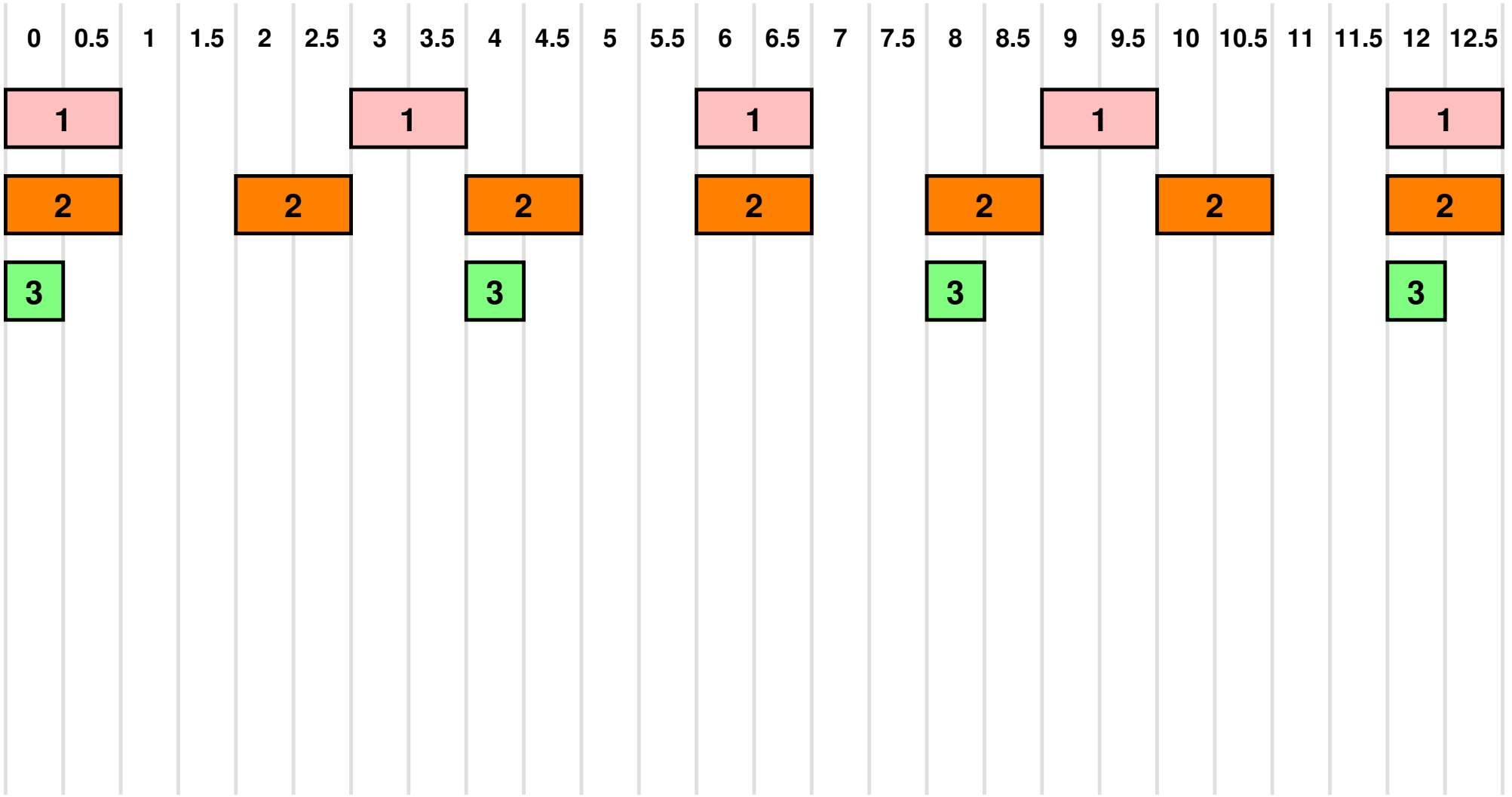


Making It Work: How Many Tickets?

- MP3 player requires 1/4 of processor time
  - 2 tickets
  - guaranteed 1/4 of processor time
- Streaming video player requires 3/8 of processor time
  - 3 tickets
  - guaranteed 3/8 of processor time
- OS project can use all of processor time, but usually much less
  - 3 tickets
  - guaranteed 3/8 of processor time

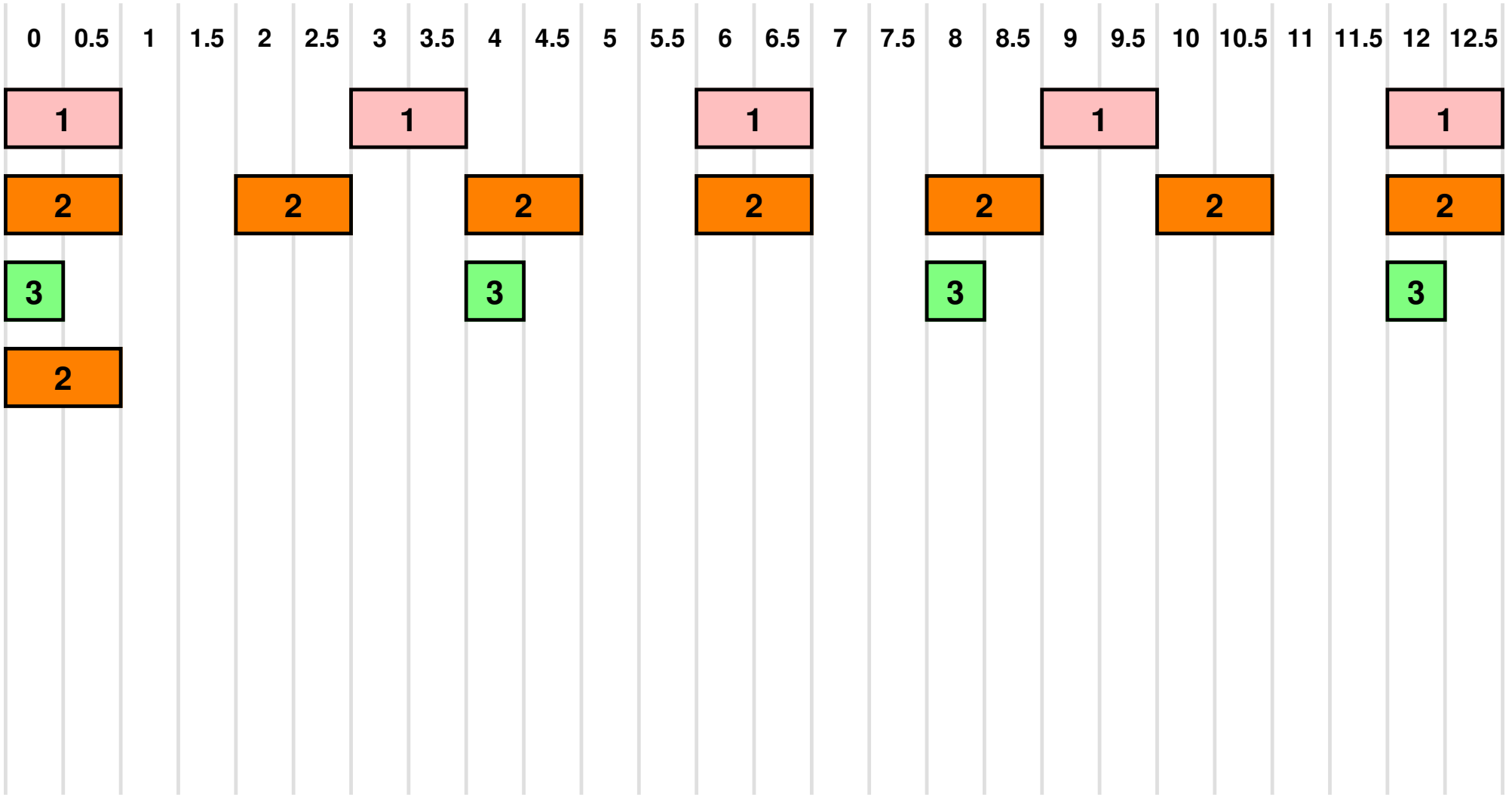


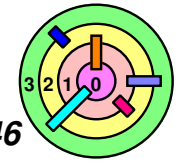
Phase Problems



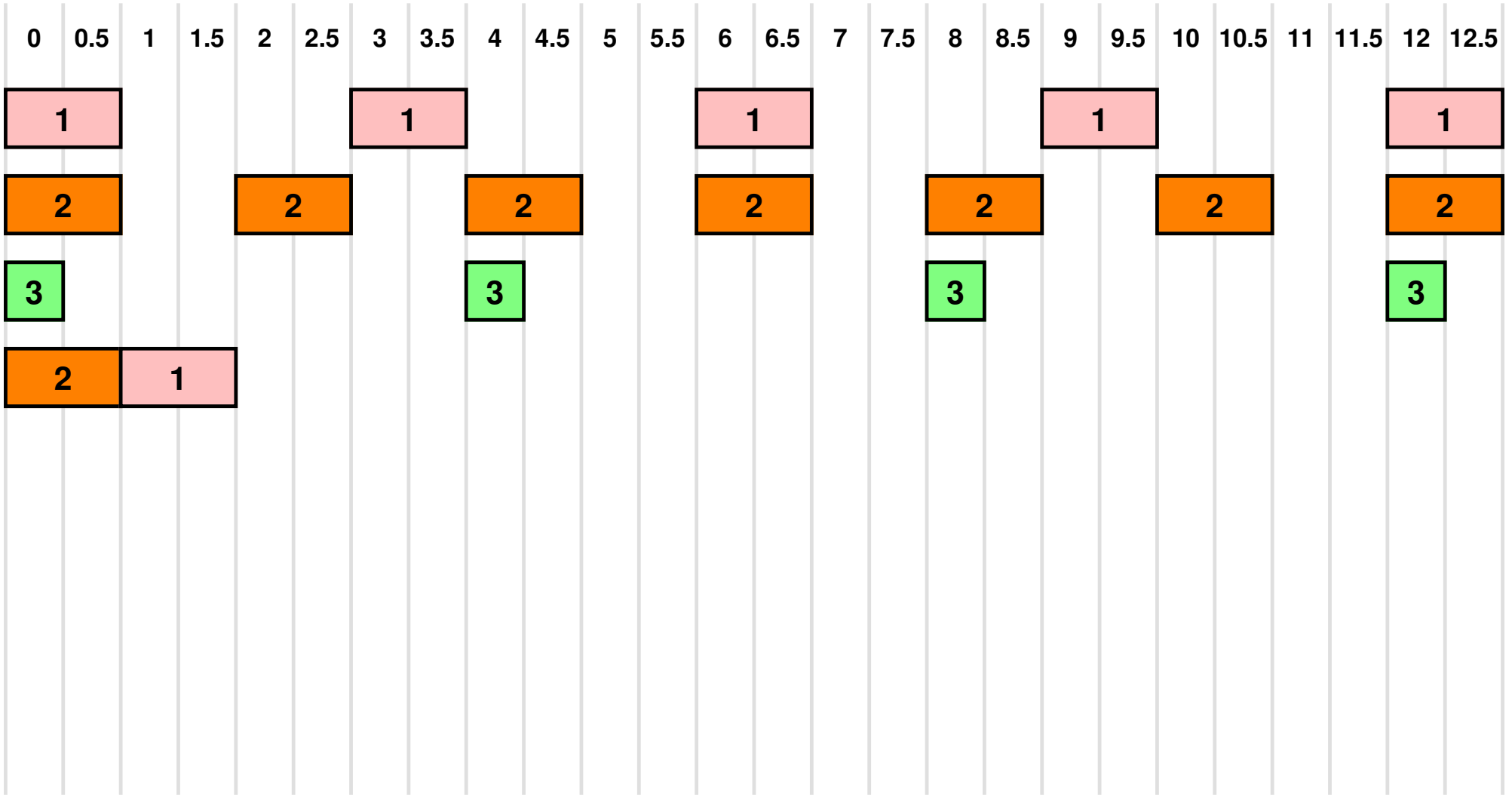
see "extra slides" at the end

Phase Problems

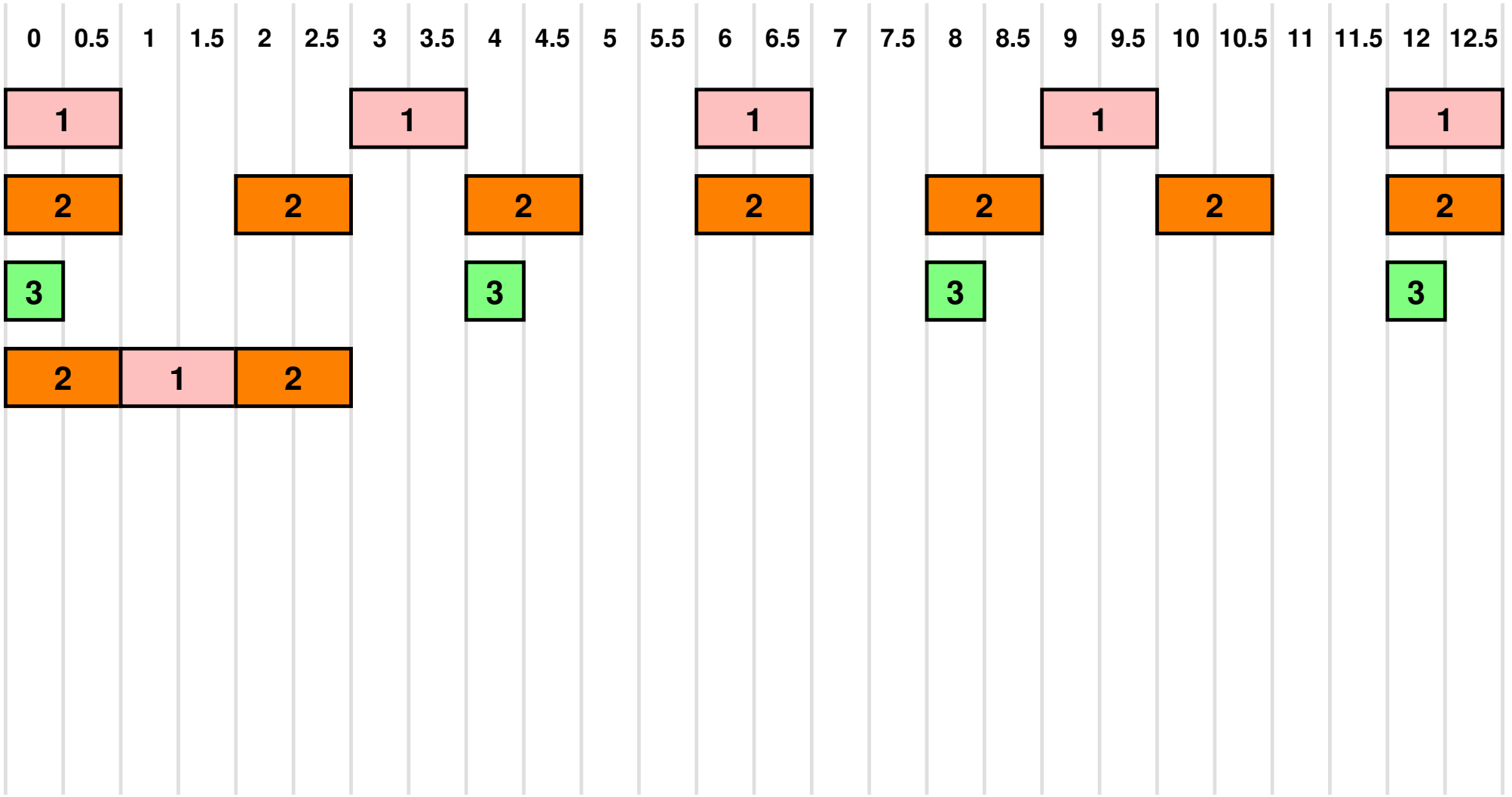




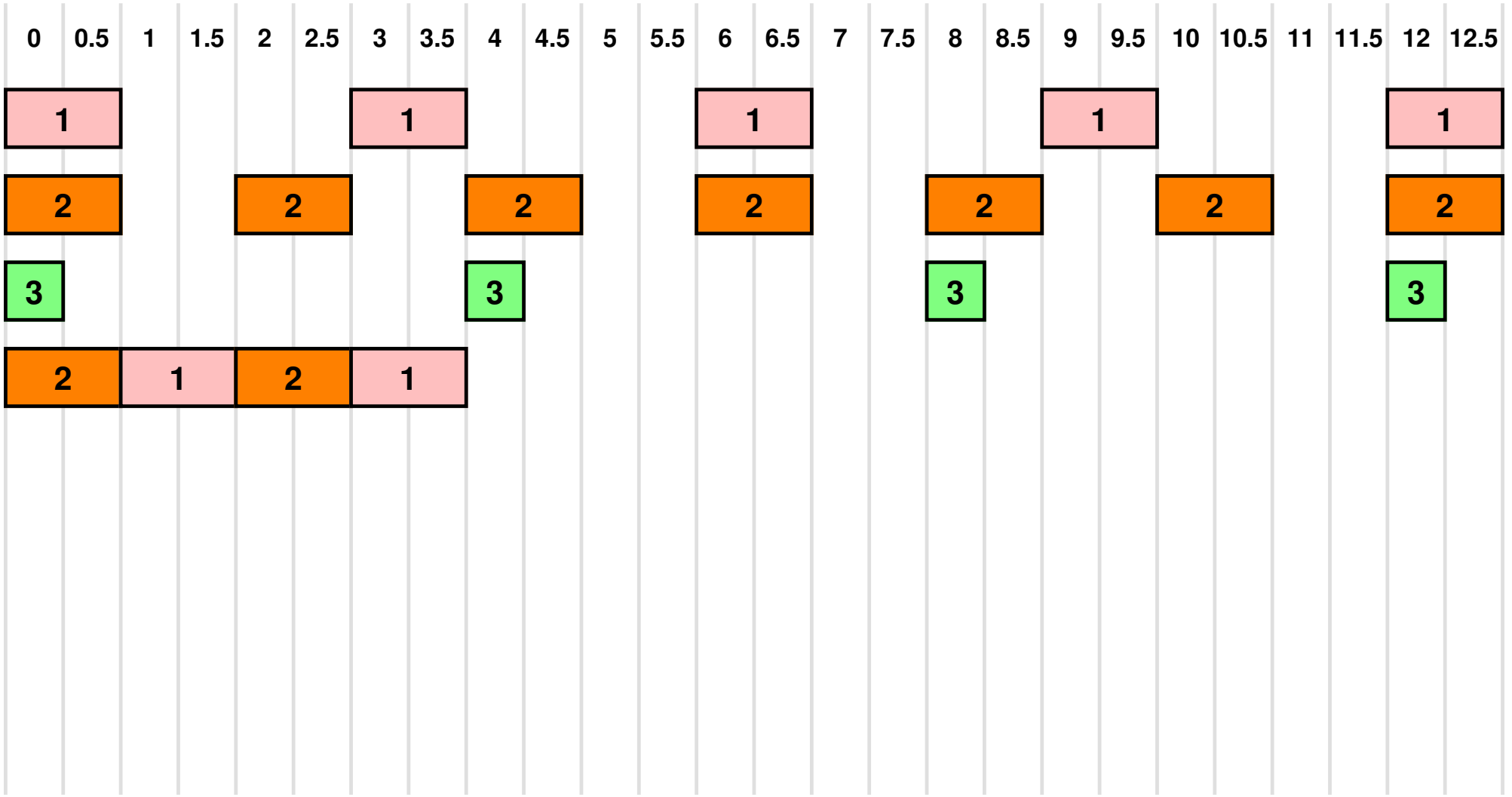
Phase Problems



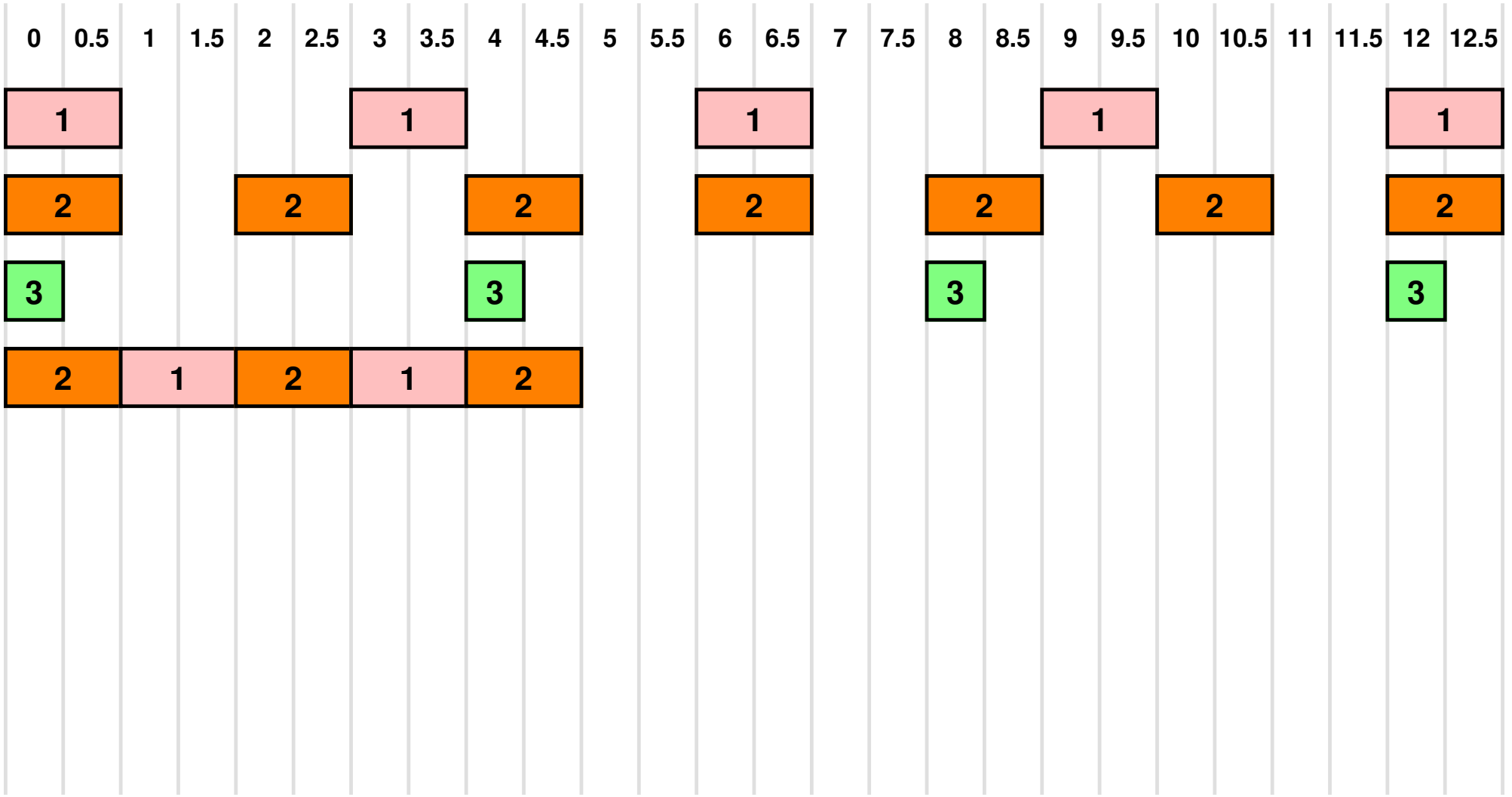
Phase Problems



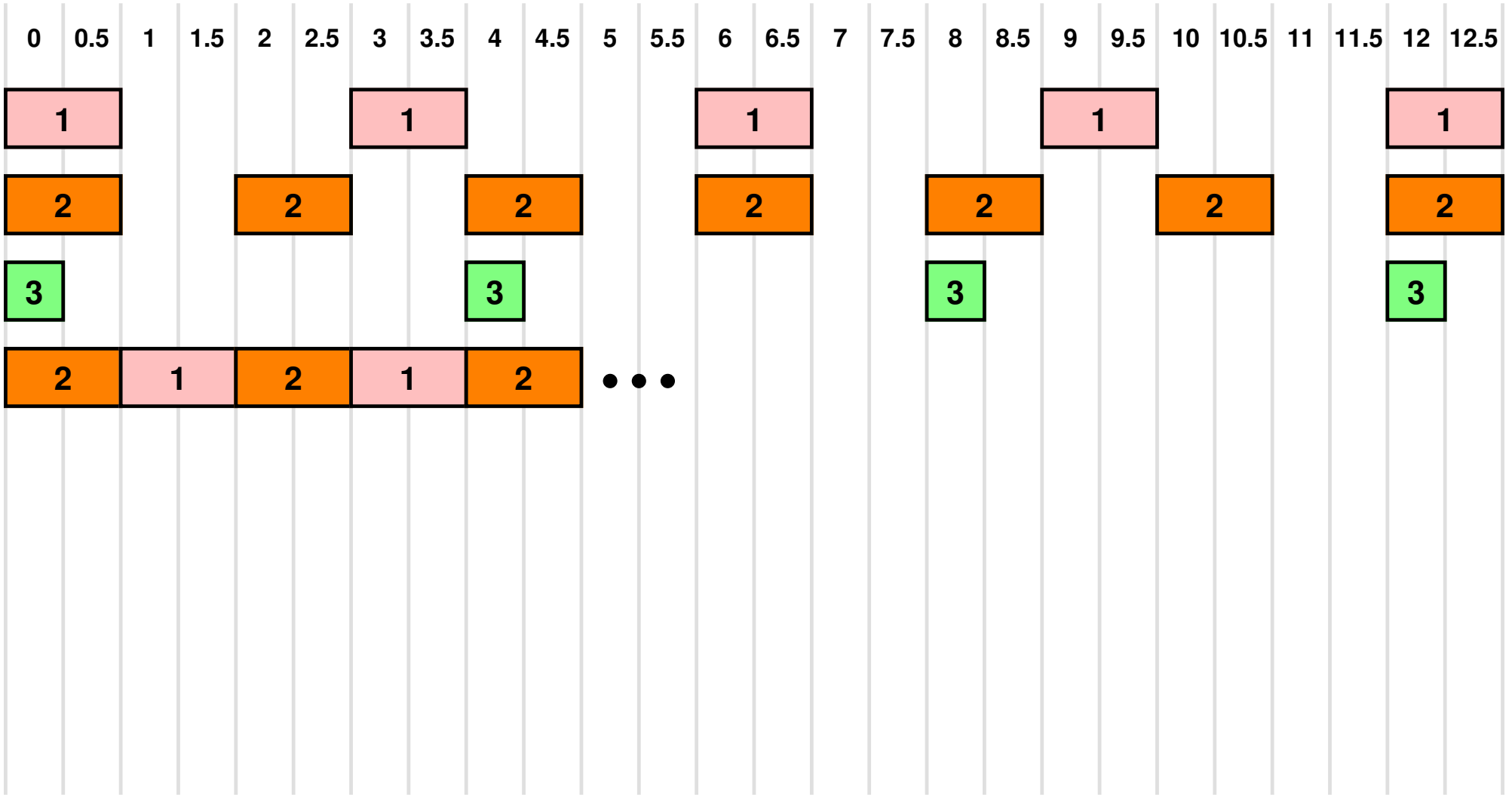
Phase Problems



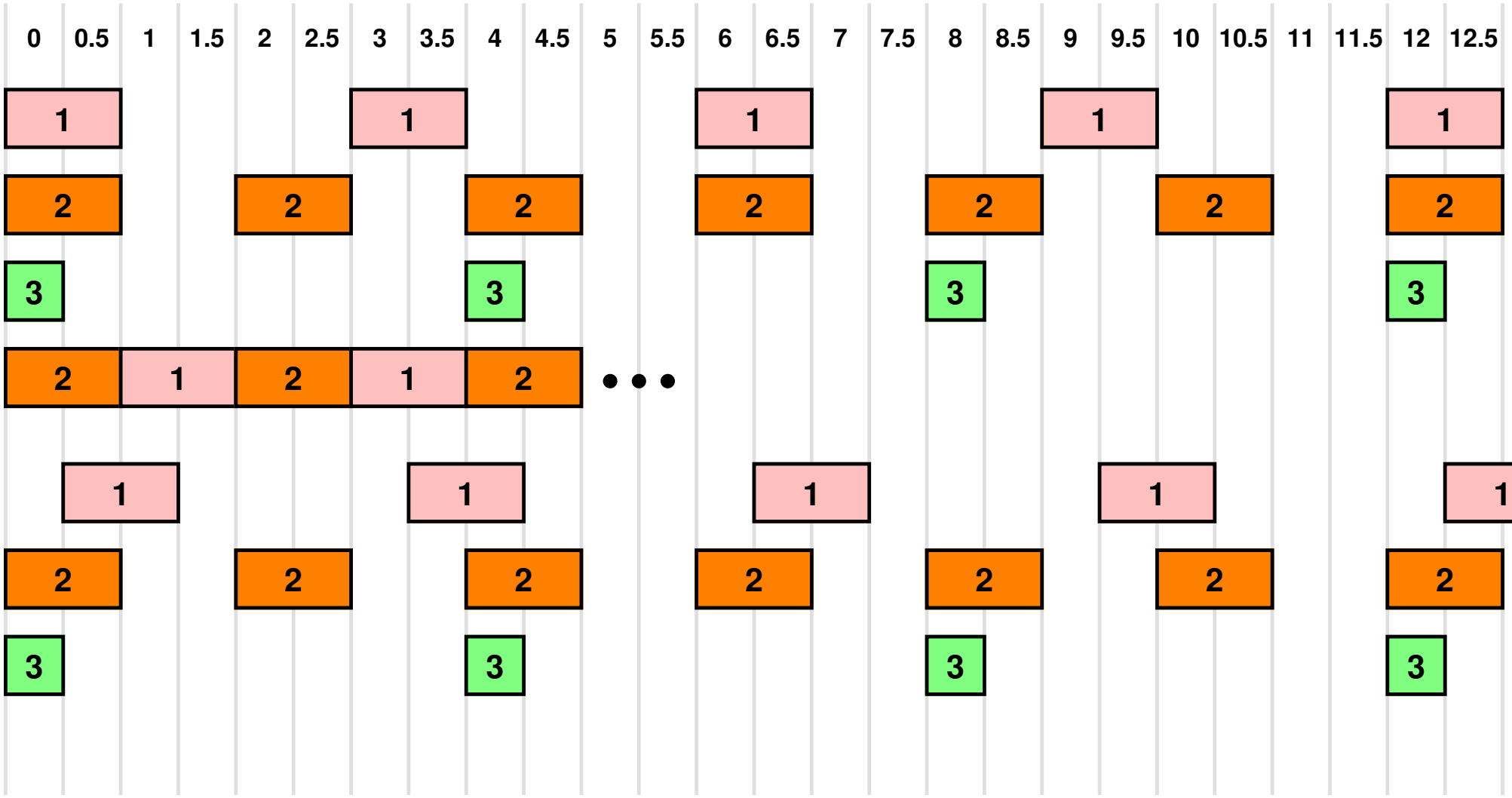
Phase Problems



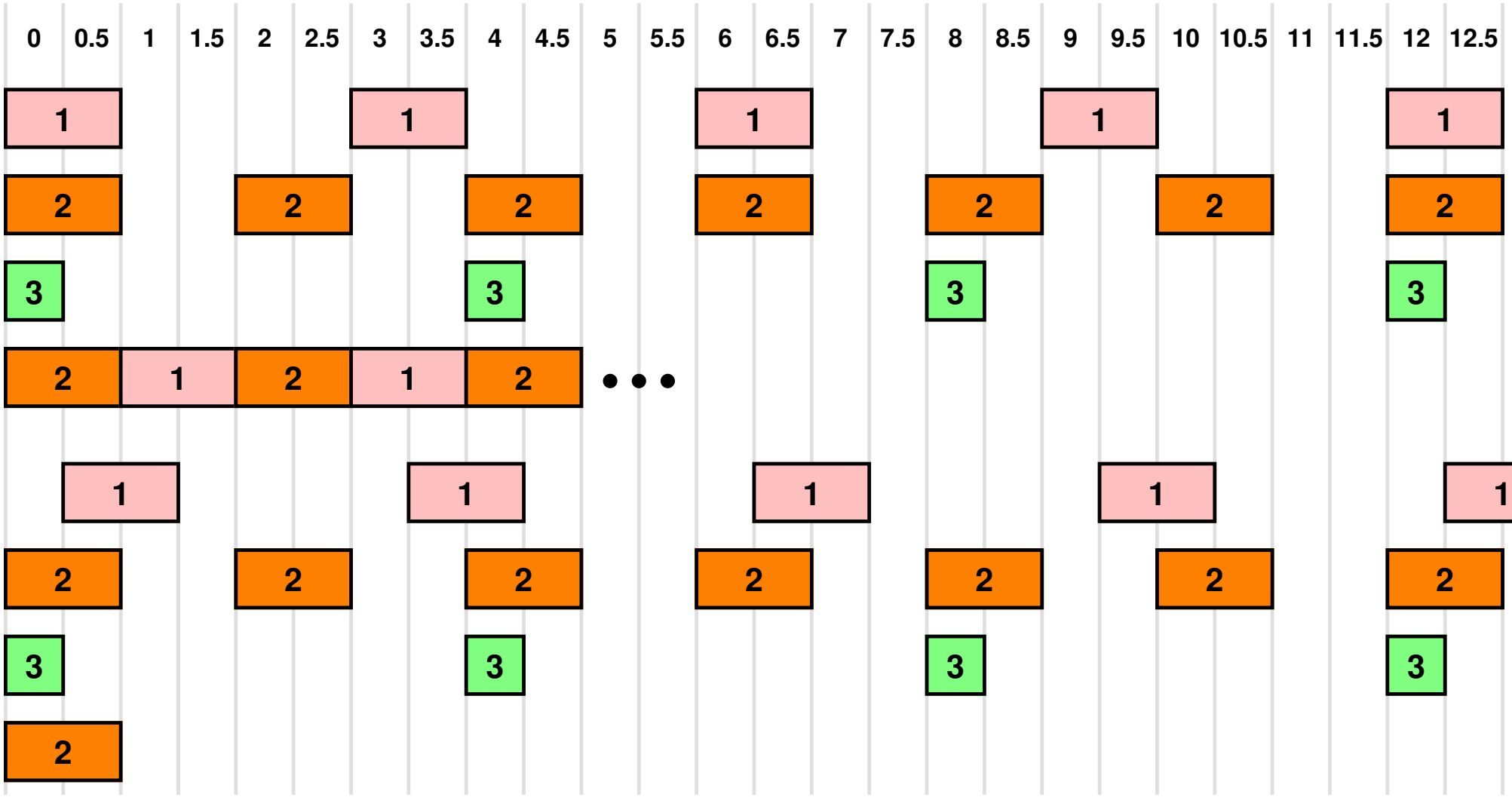
Phase Problems



Phase Problems



Phase Problems



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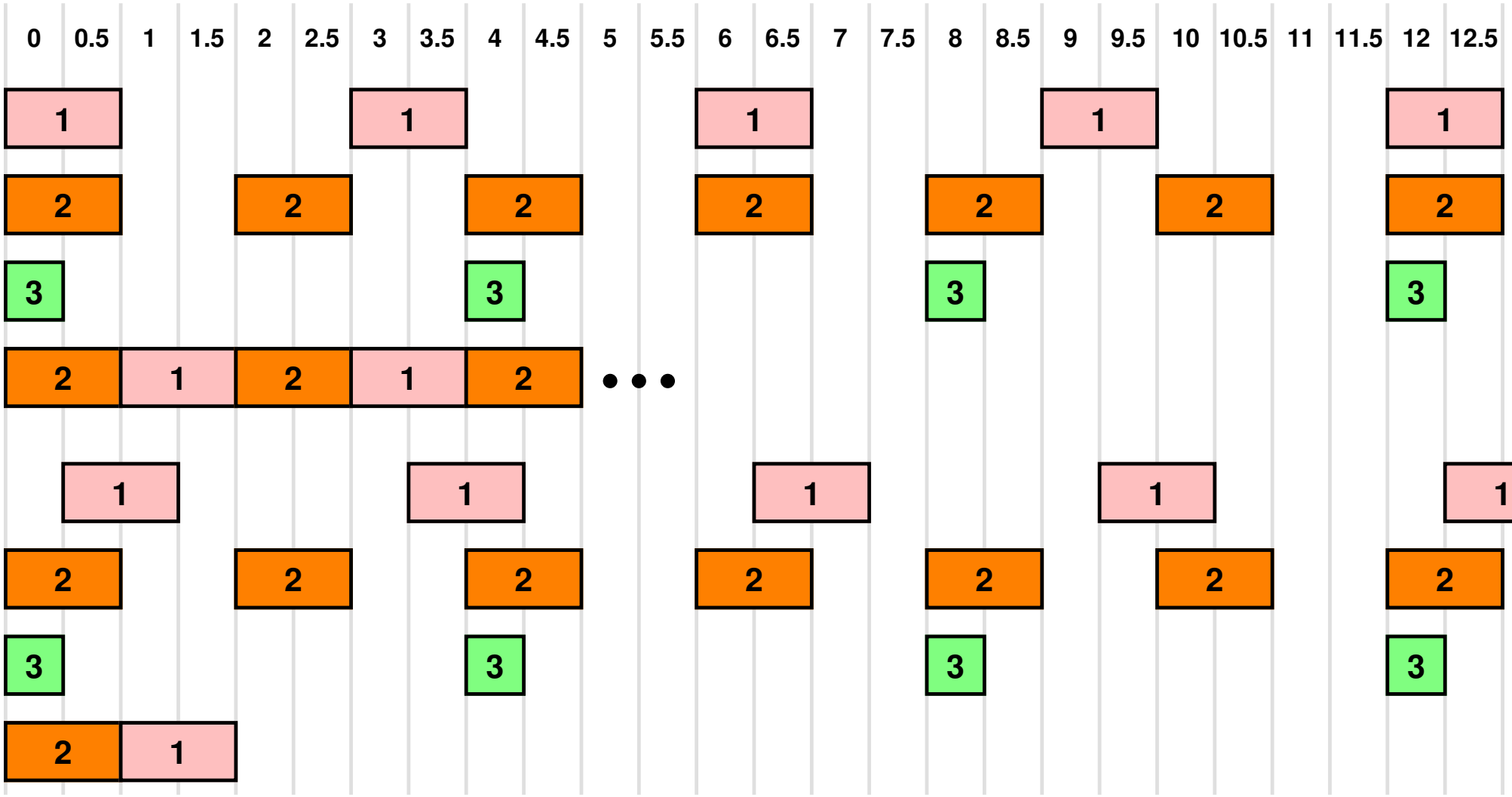
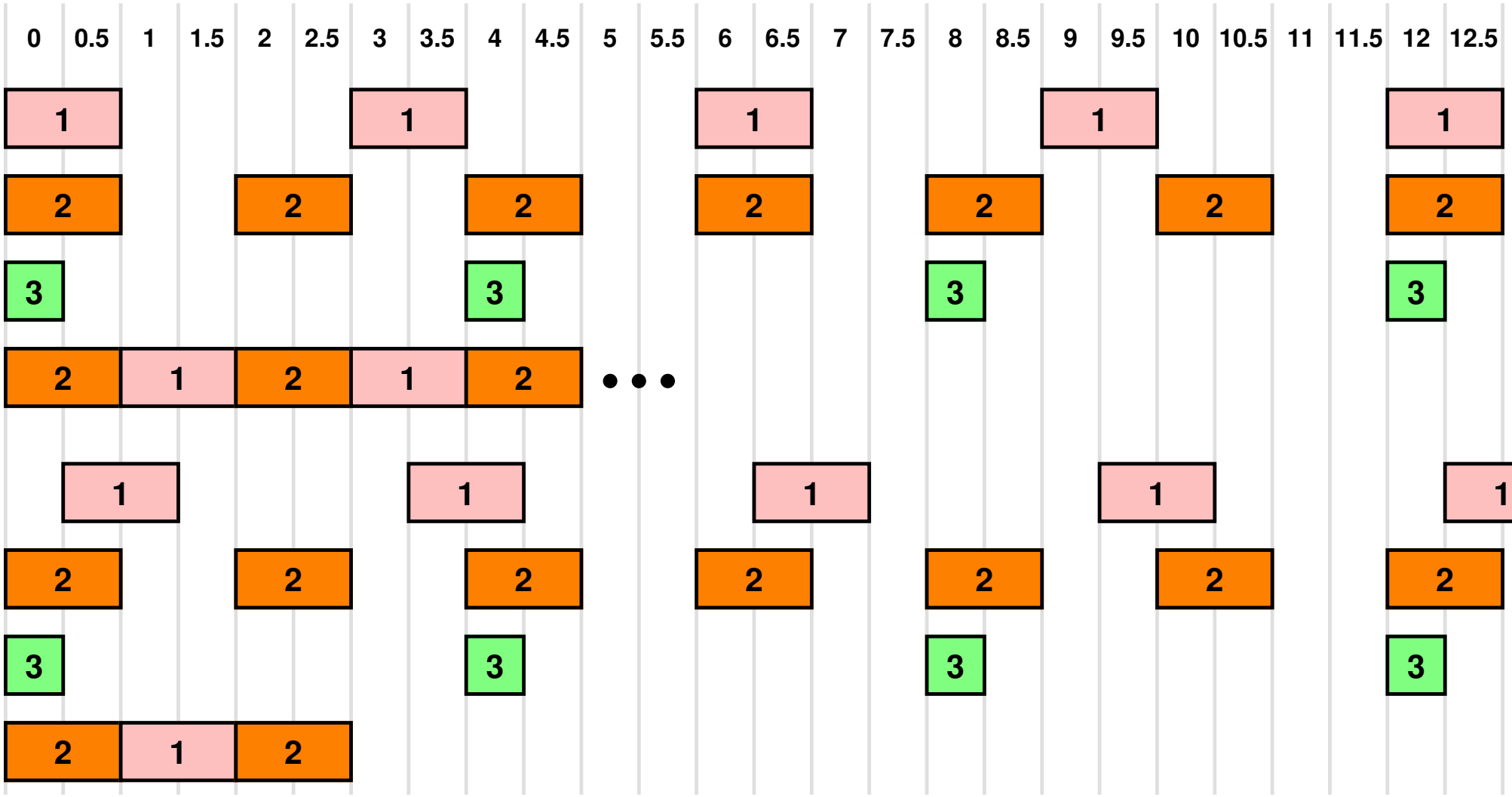
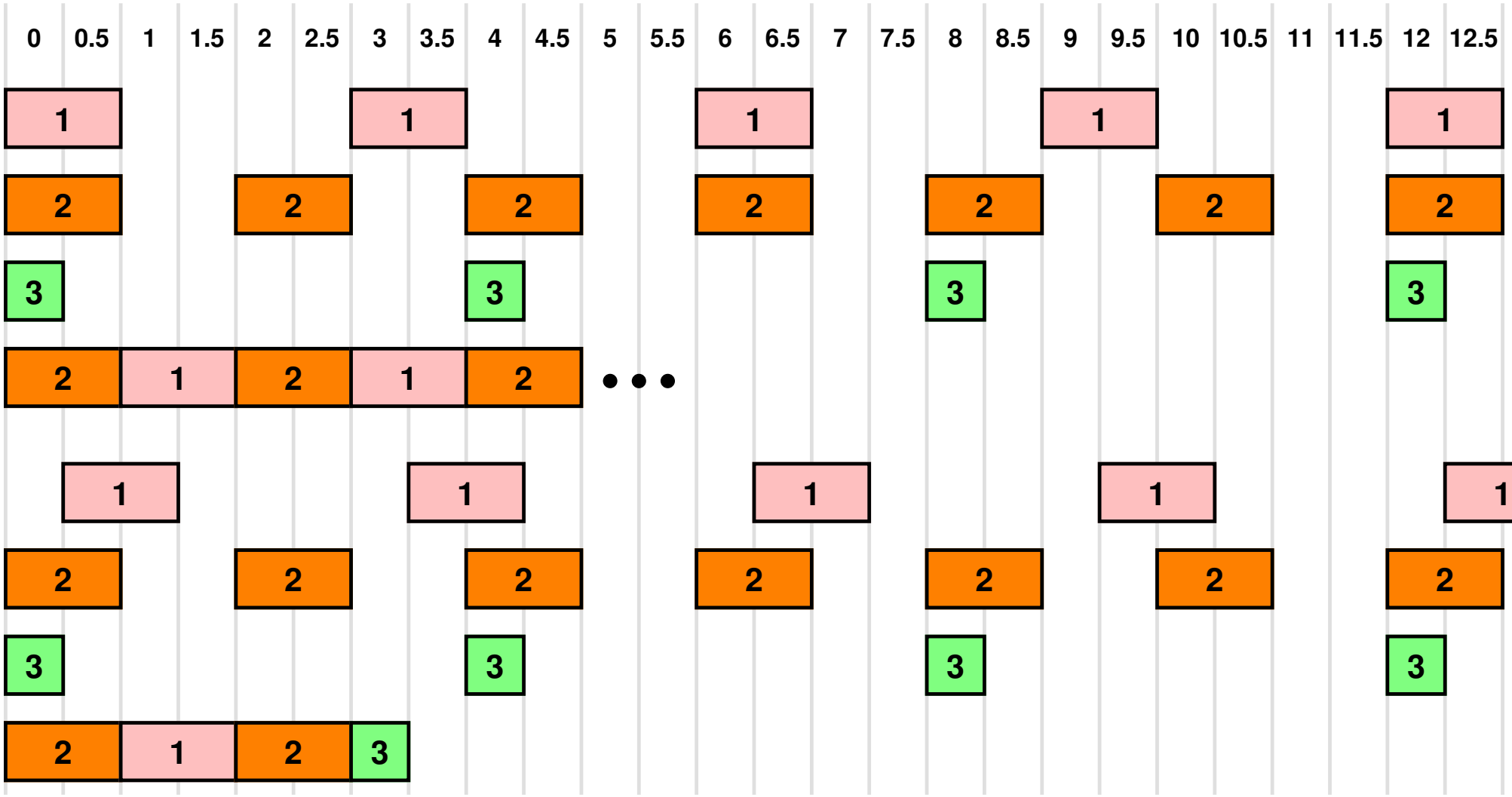


Phase Problems



Phase Problems



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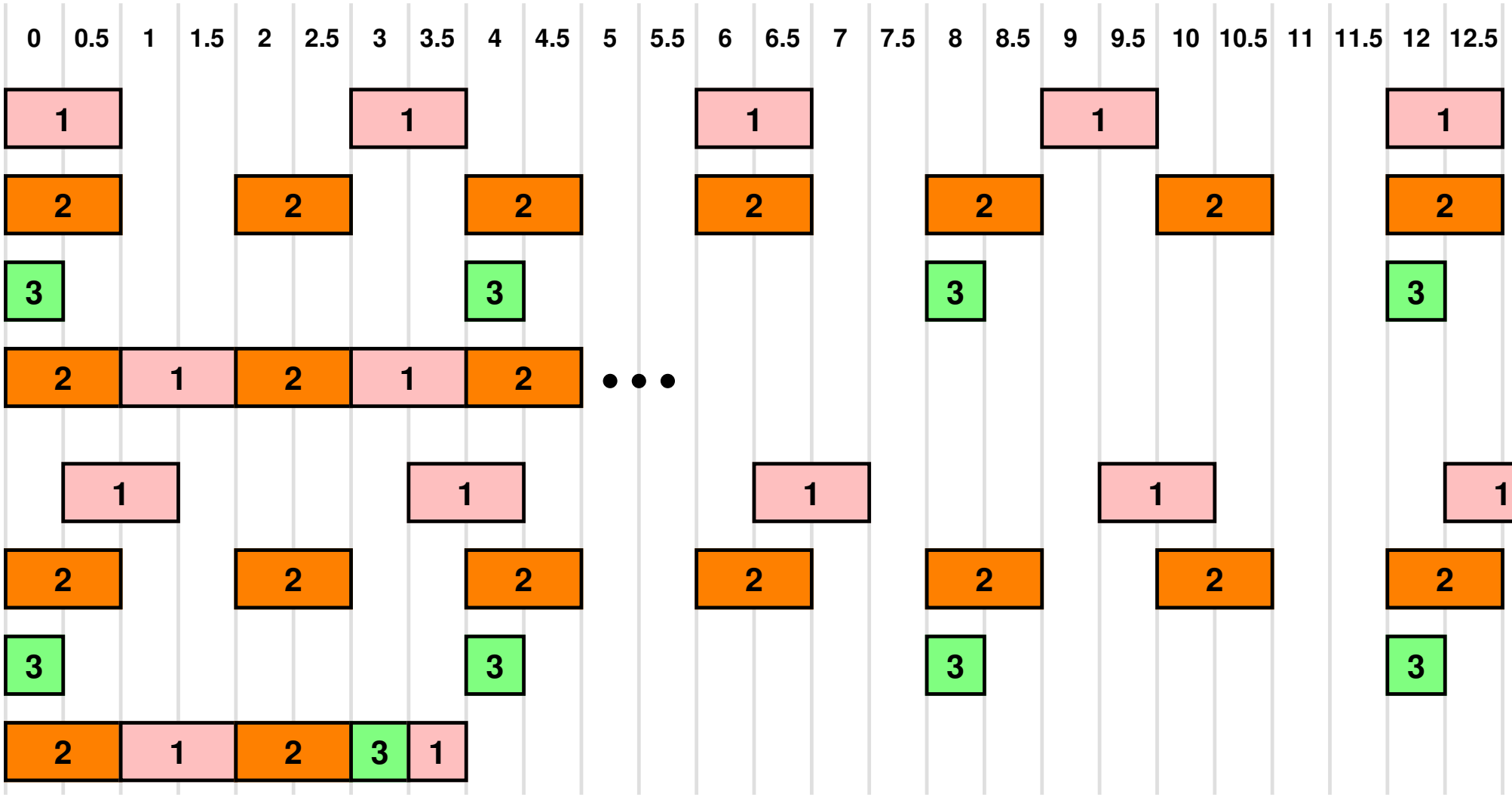

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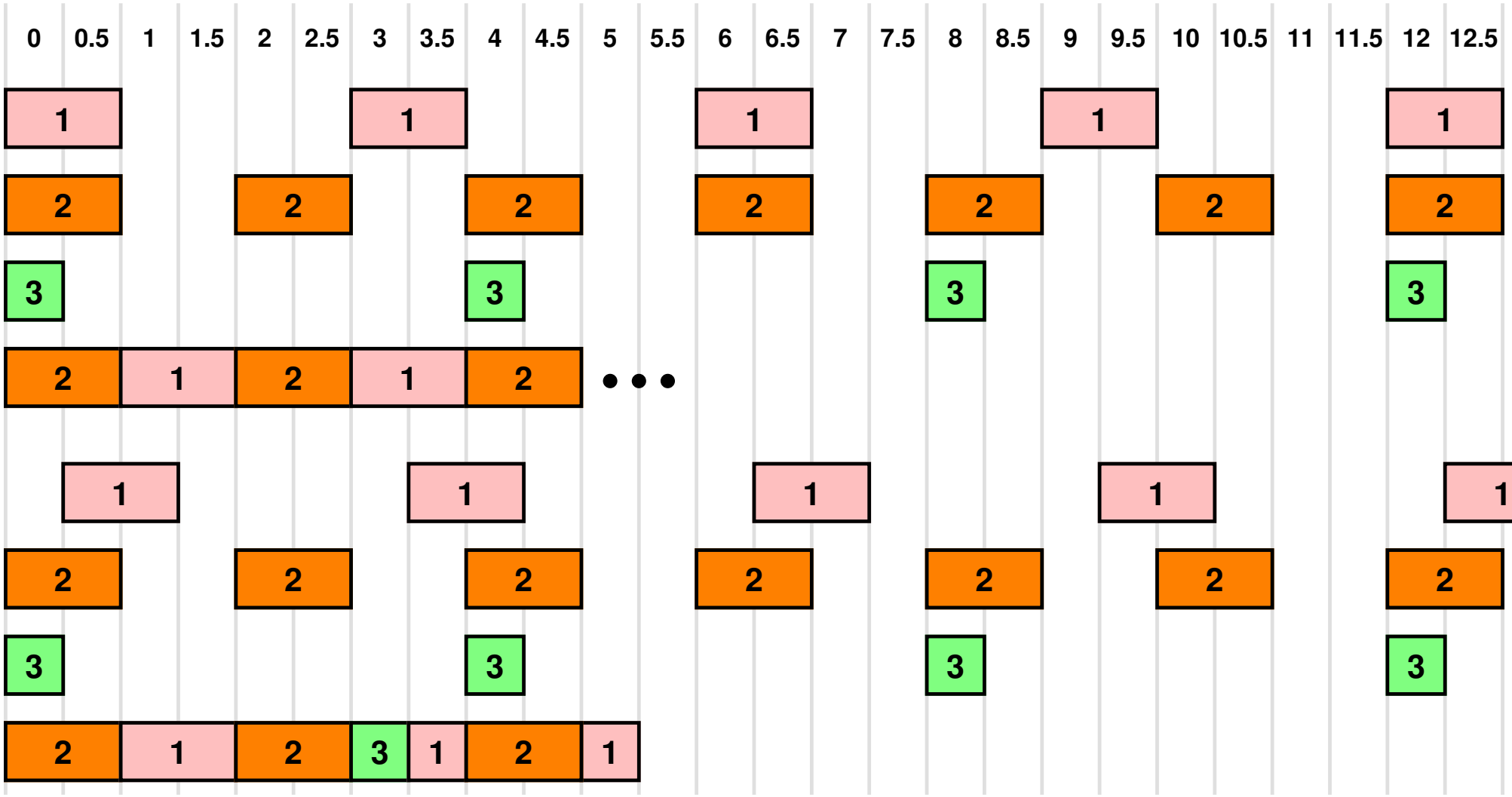

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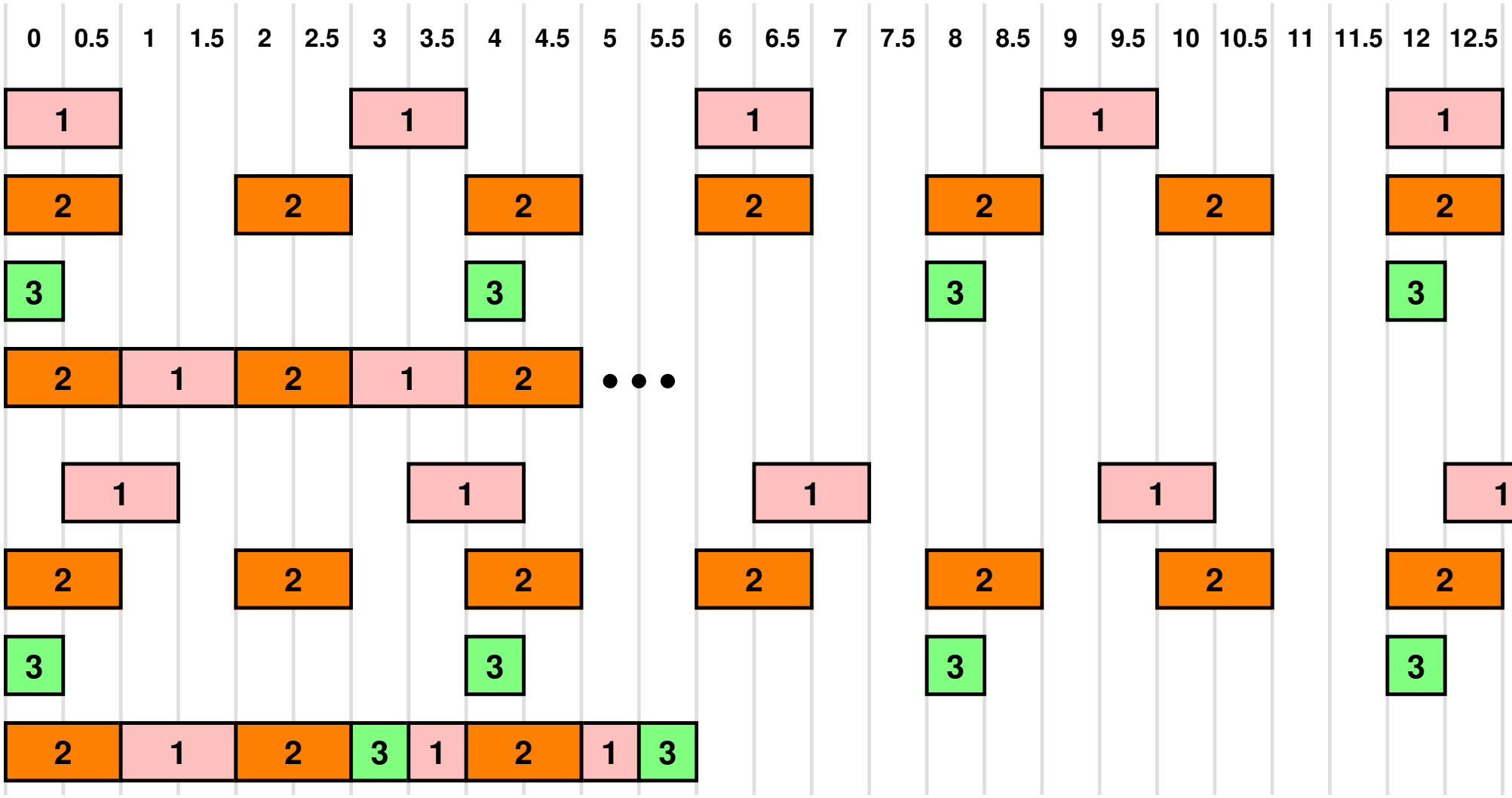

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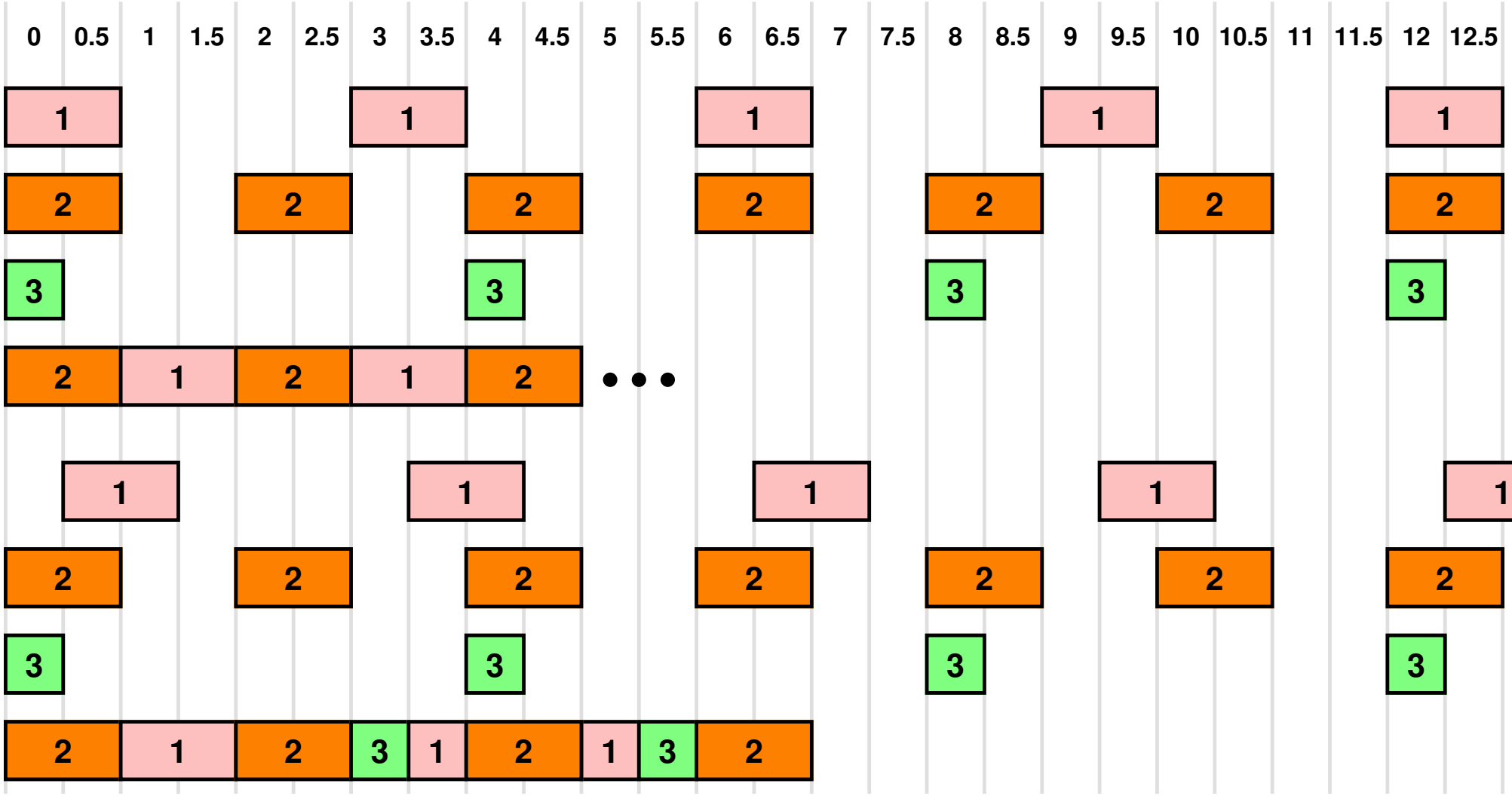

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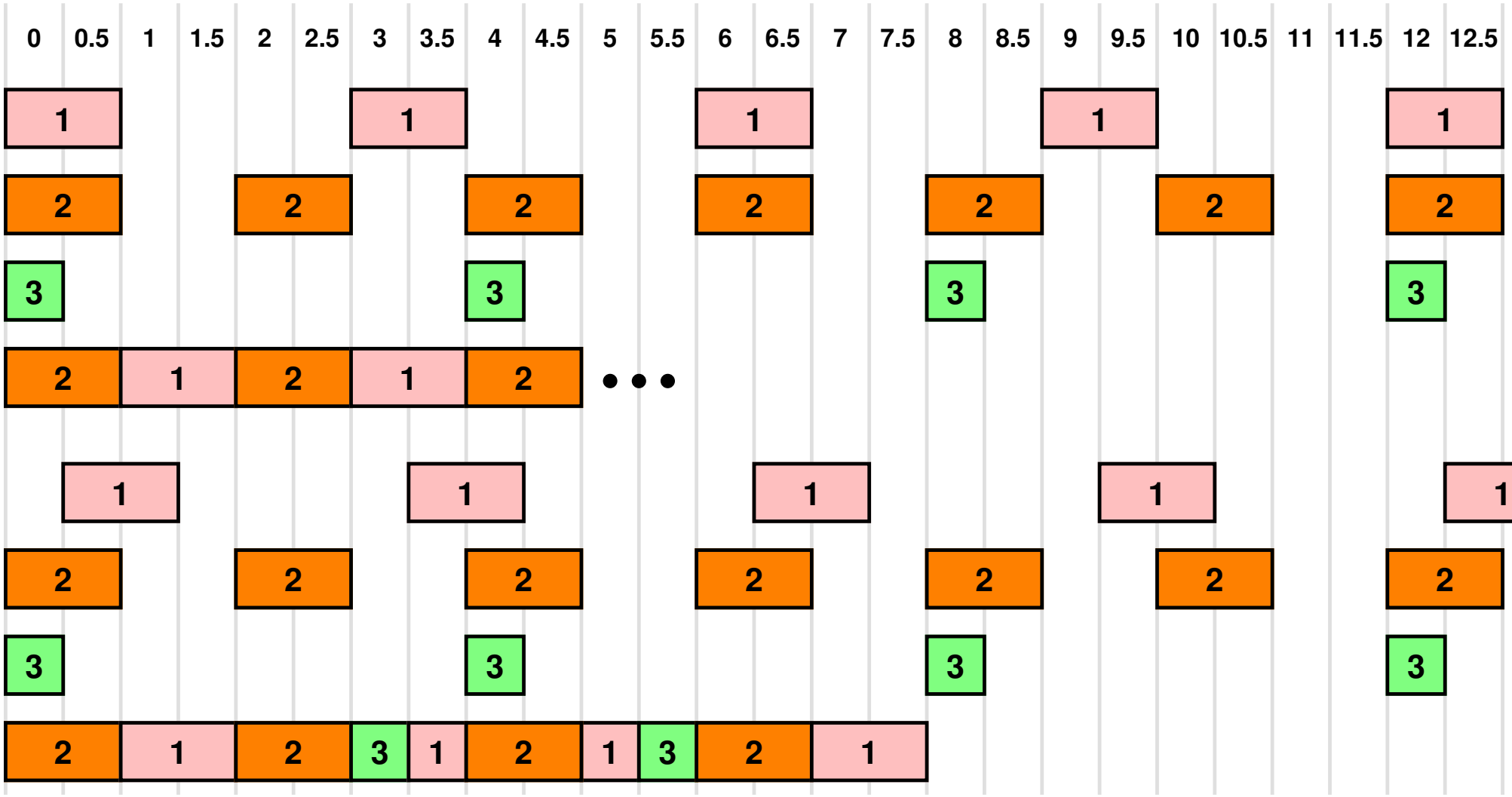

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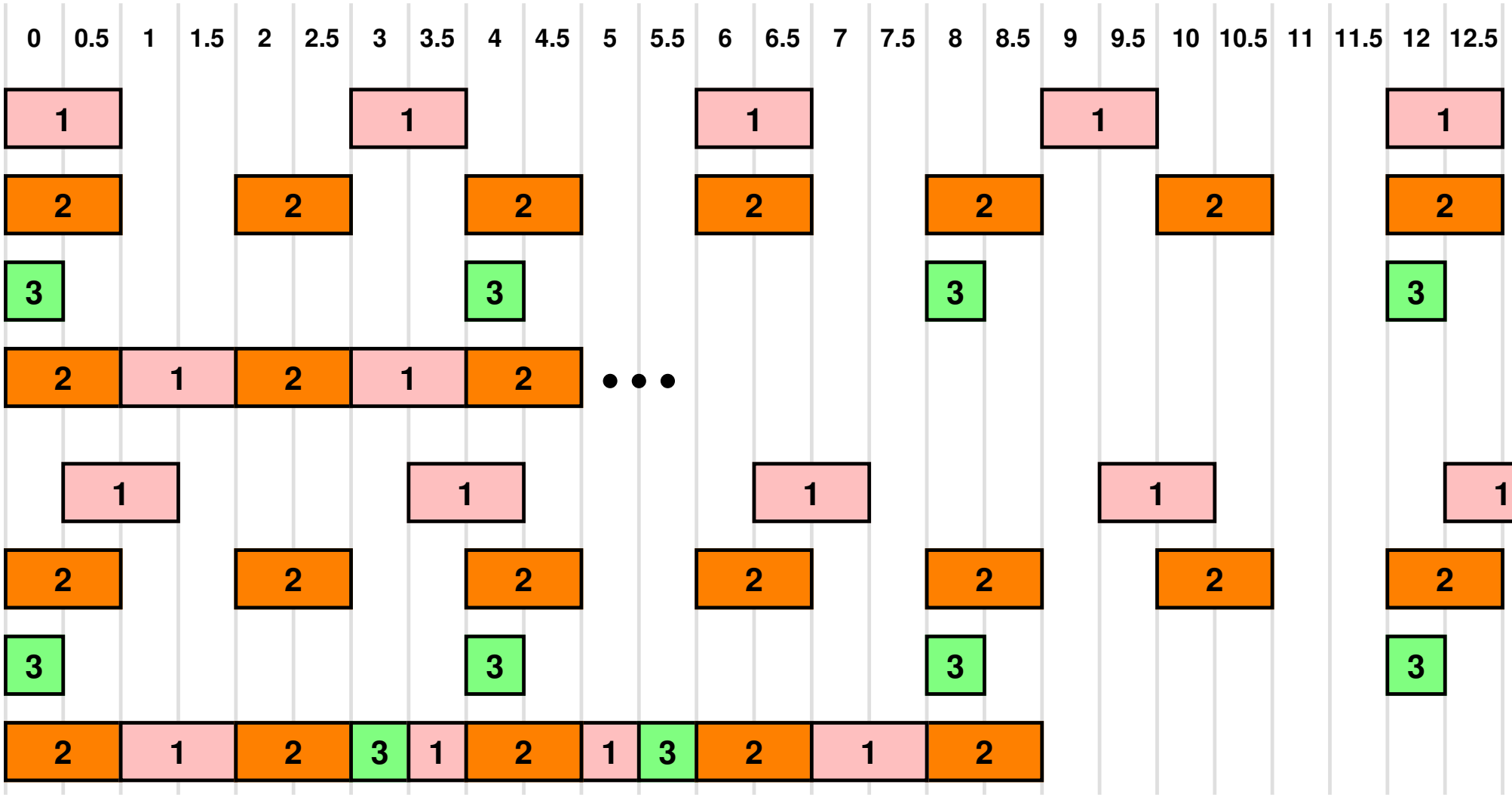
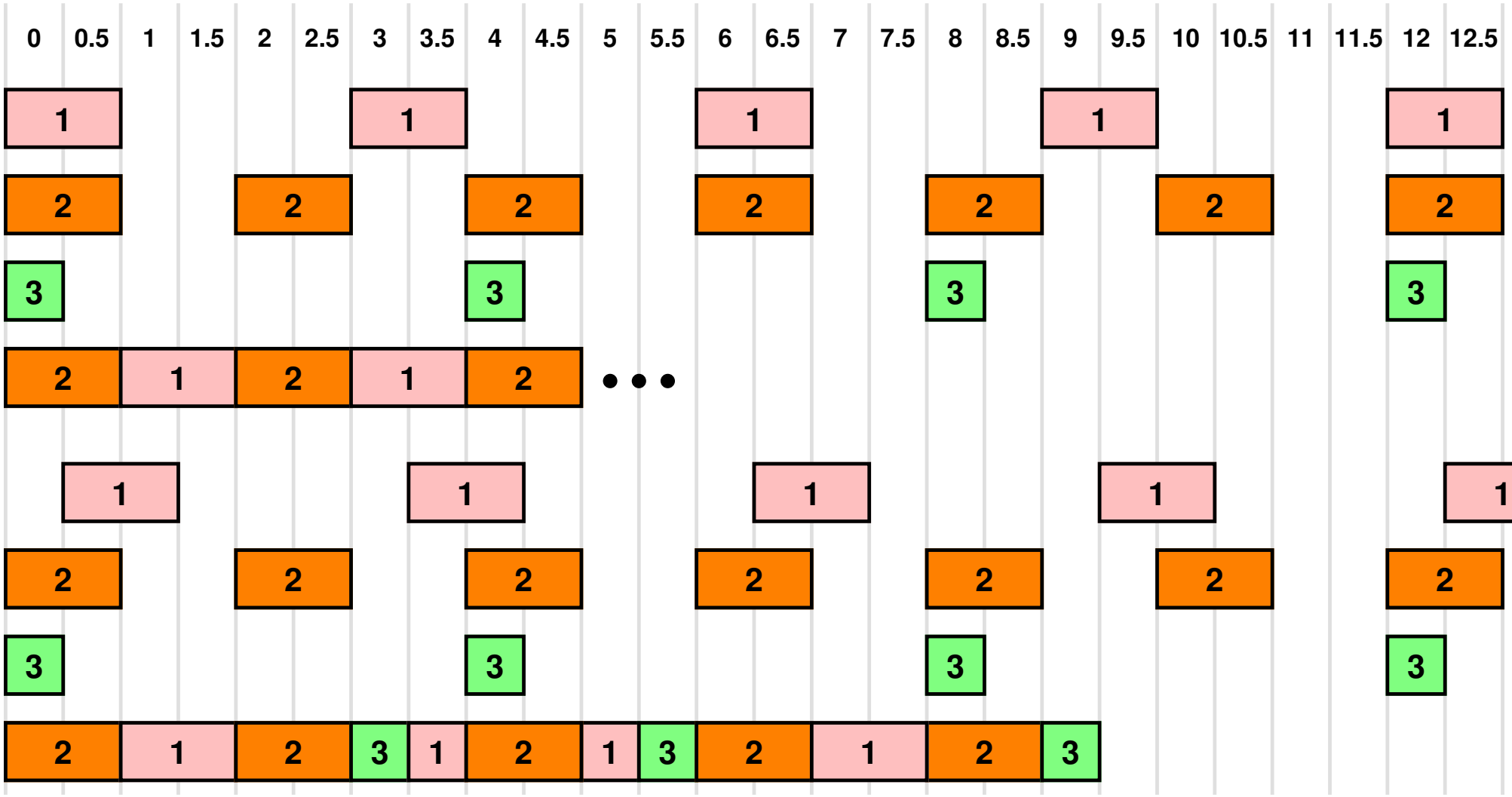


Phase Problems



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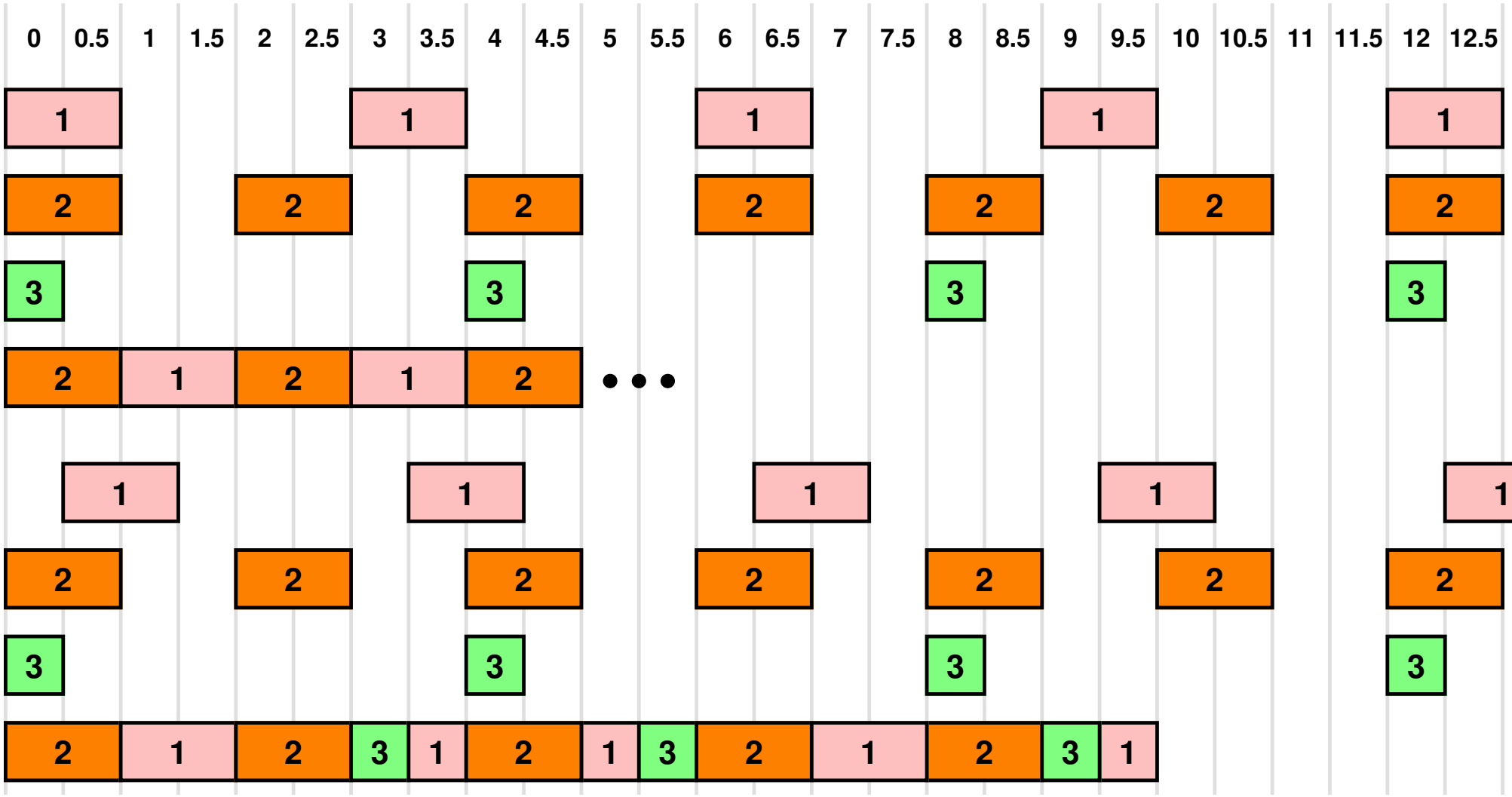

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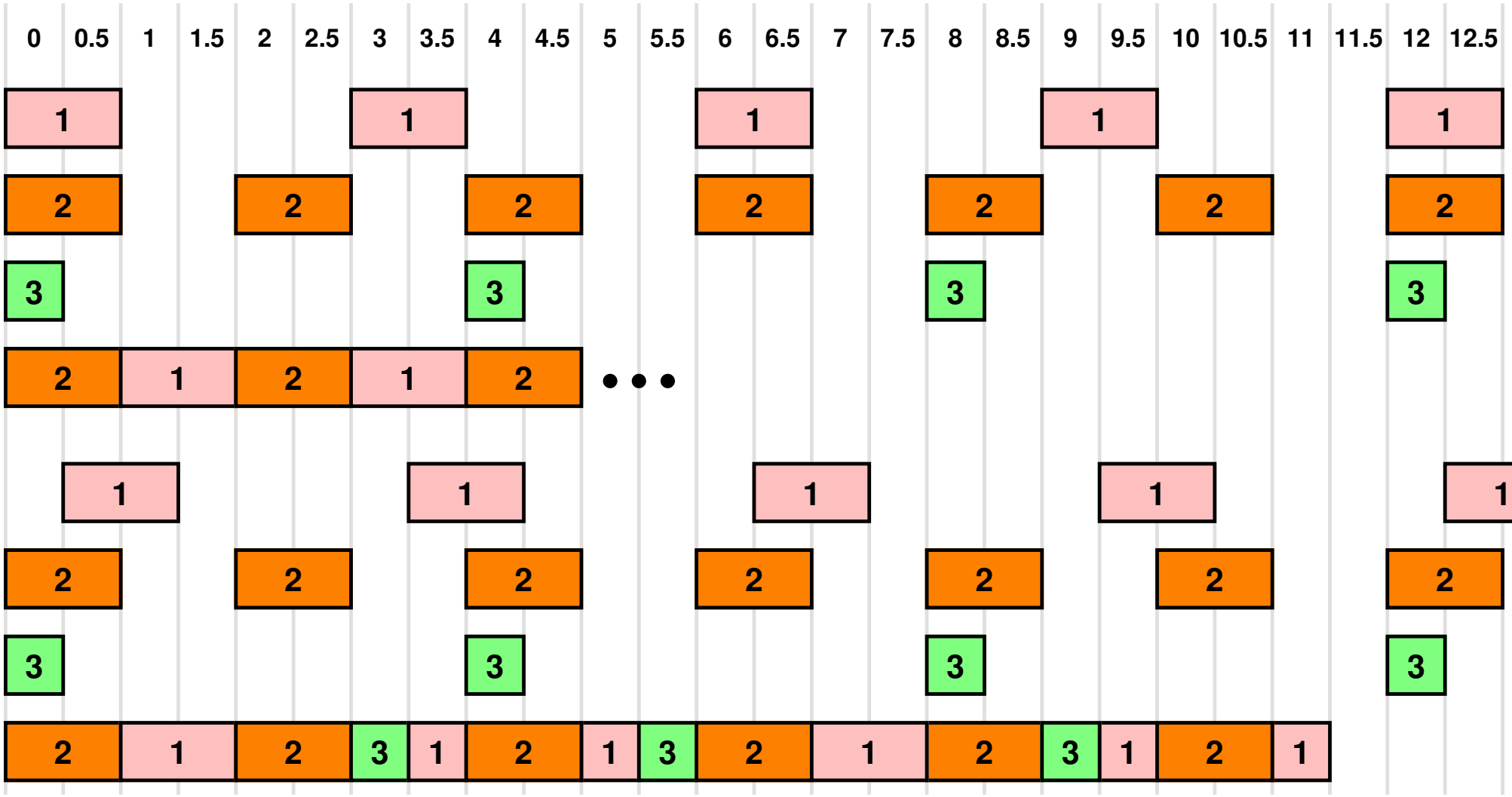

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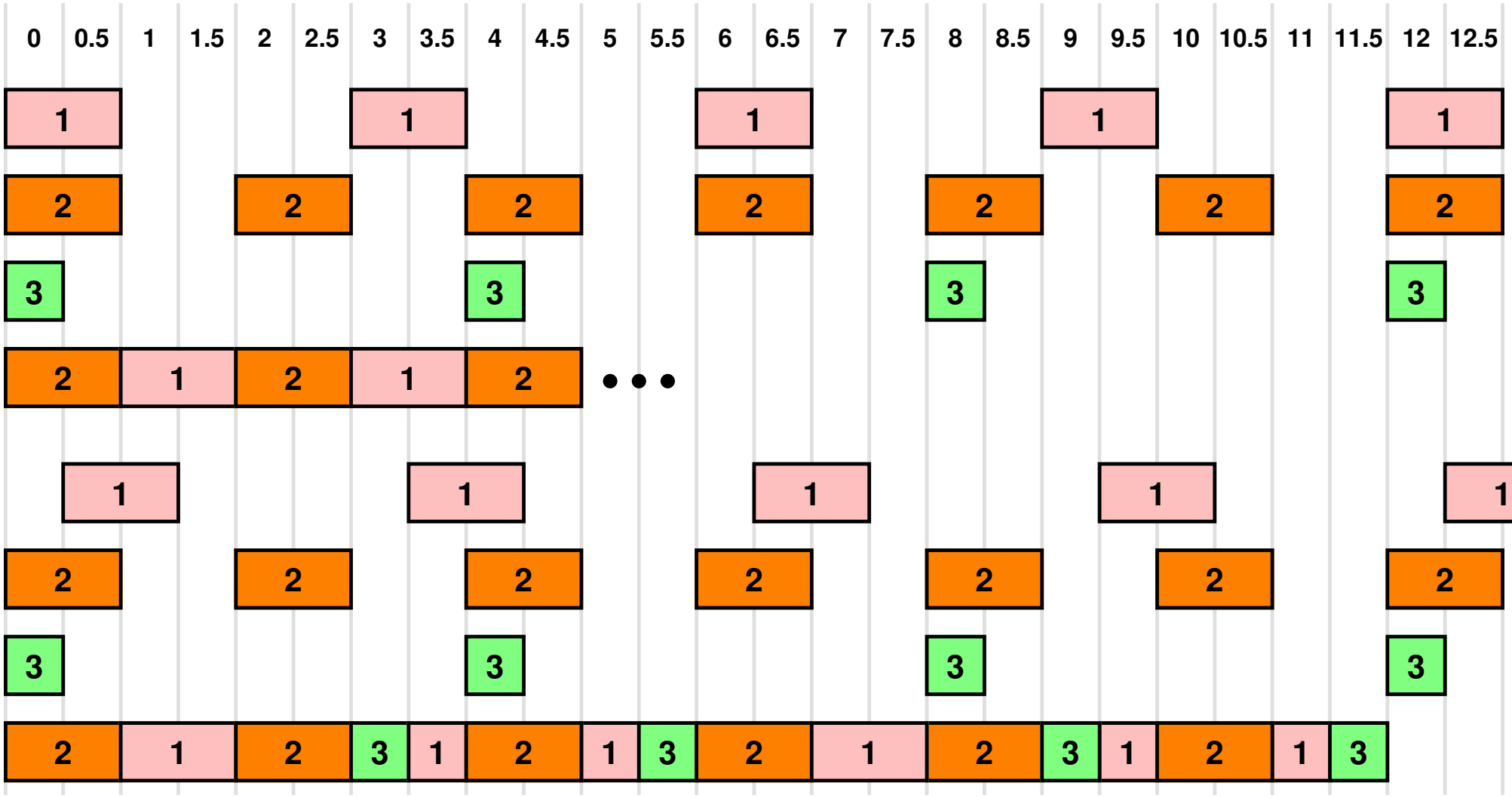
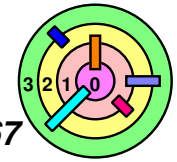


Old Scheduler

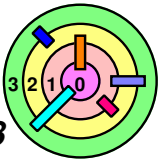
- Four per-process scheduling variables
  - *policy:* which one
  - *rt_priority:* real-time priority
    - 0 for SCHED_OTHER
    - 1 - 99 for others
  - *priority:* time-slice parameter ("nice" value)
  - *counter:* records processor consumption

- see "extra slides" at the end



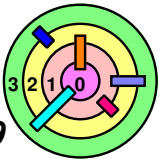
Old Scheduler: Time Slicing

- Clock "ticks" HZ times per second
  - interrupt/tick
- Per-process *counter*
  - current process's is decremented by one each tick
  - time slice over when counter reaches 0



Old Scheduler: Throughput

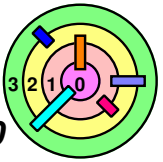
- Scheduling cycle
  - length, in "ticks", is sum of priorities
  - each process gets *priority* ticks/cycle
    - *counter* set to *priority*
    - cycle over when *counters* for runnable processes are all 0
  - sleeping processes get "boost" at wakeup
    - at beginning of each cycle, for each process:
      - counter = counter/2 + priority



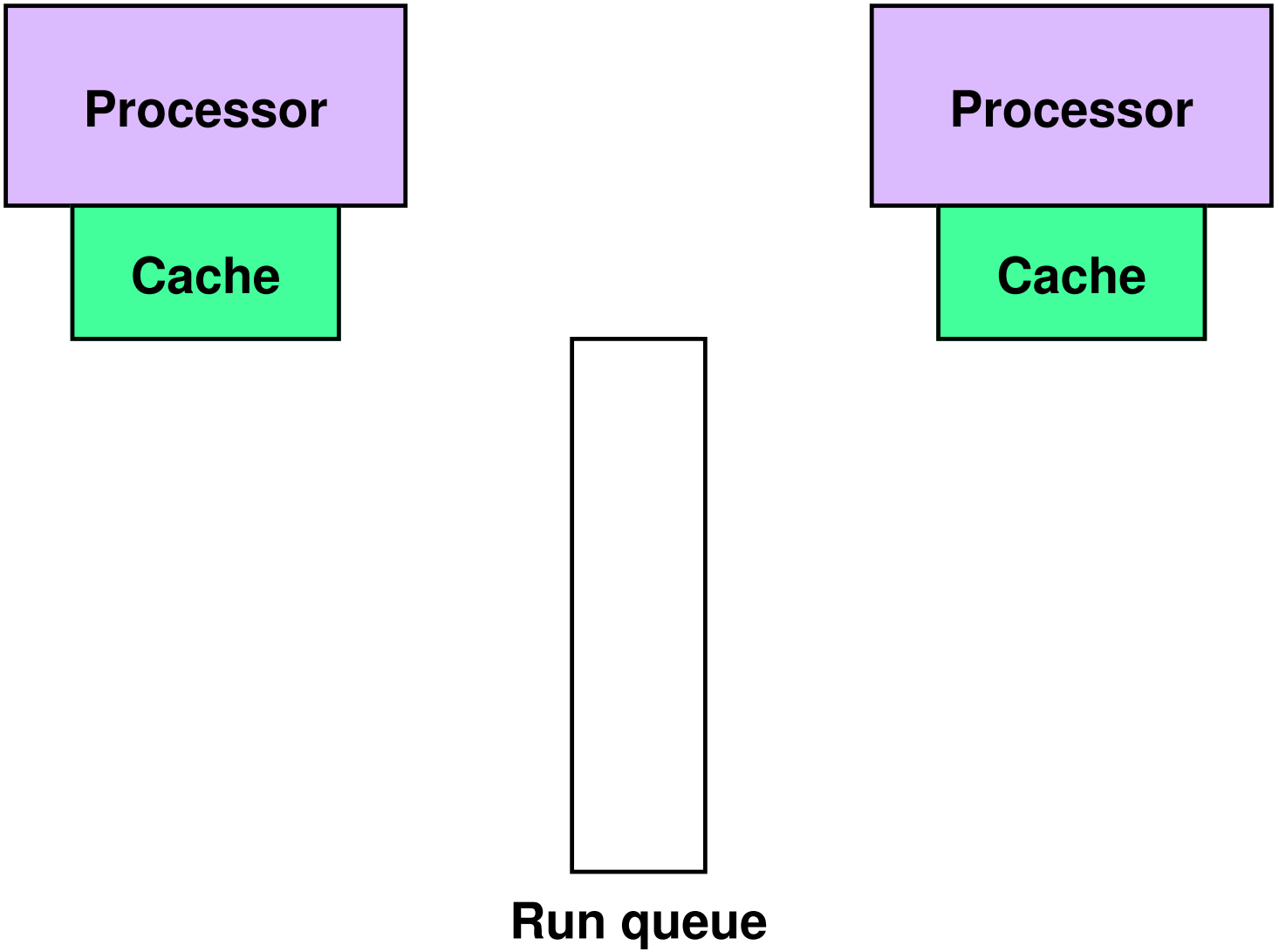
Old Scheduler: Who's Next?

- Run queue searched beginning to end
  - new arrivals go to front
  - SCHED_RR processes go to end at completion of time slices

- Next running process is first process with highest "goodness"
  - 1000 + rt_priority for SCHED_FIFO and SCHED_RR processes
  - *counter* for SCHED_OTHER processes

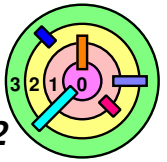


Diagram



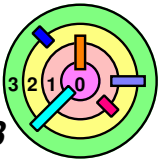
Old Scheduler: Problems

- O(n) execution
- Poor interactive performance with heavy loads
- SMP contention for run-queue lock
- SMP affinity
  - cache "footprint"
- How well does it handle the real-life example?

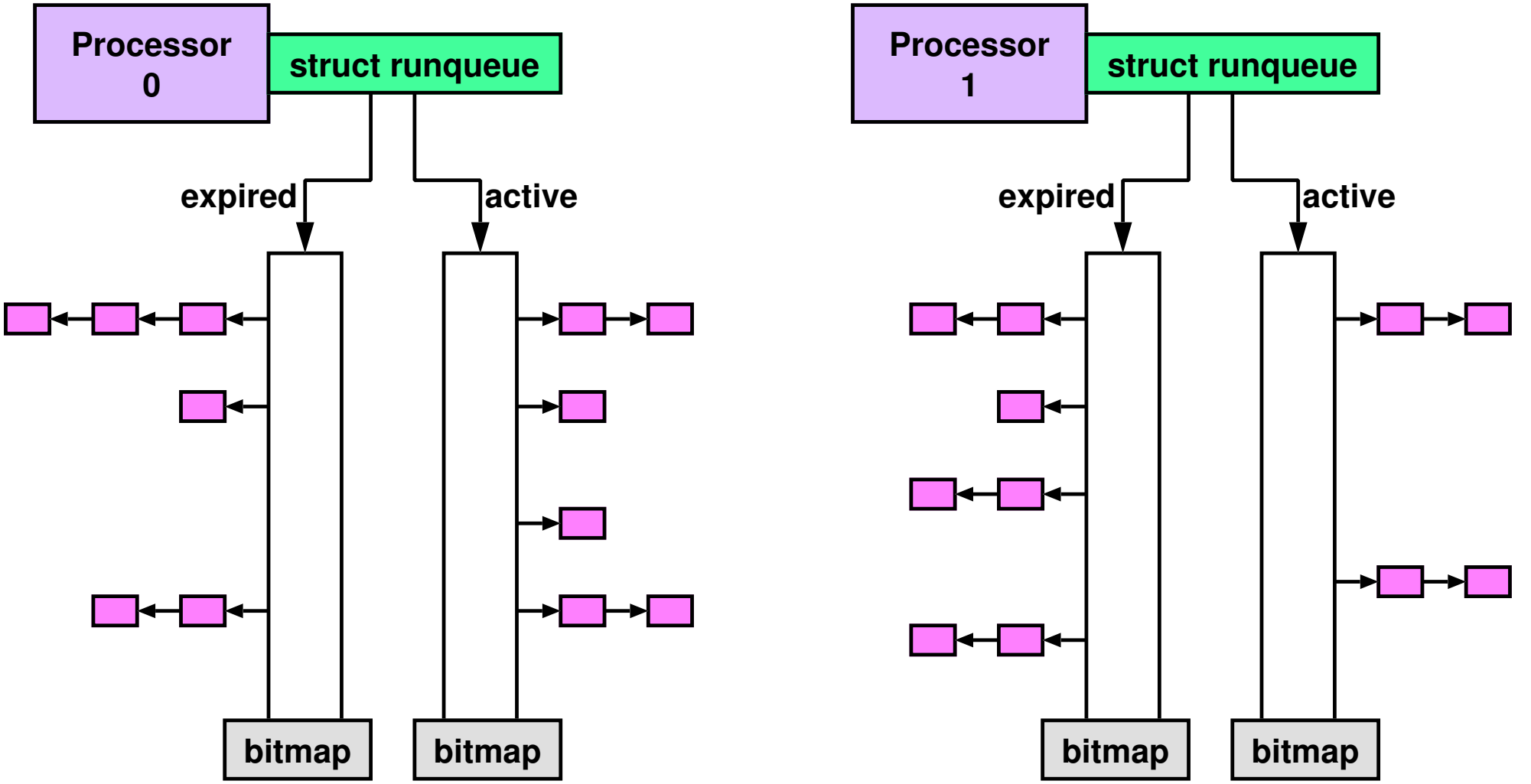


O(1) Scheduler

- All concerns of old scheduler plus:
  - efficient, scalable execution
  - identify and favor interactive processes
  - good SMP performance
    - minimal lock overhead
    - processor affinity

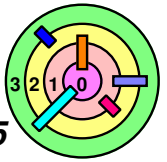


O(1) Scheduler: Data Structures

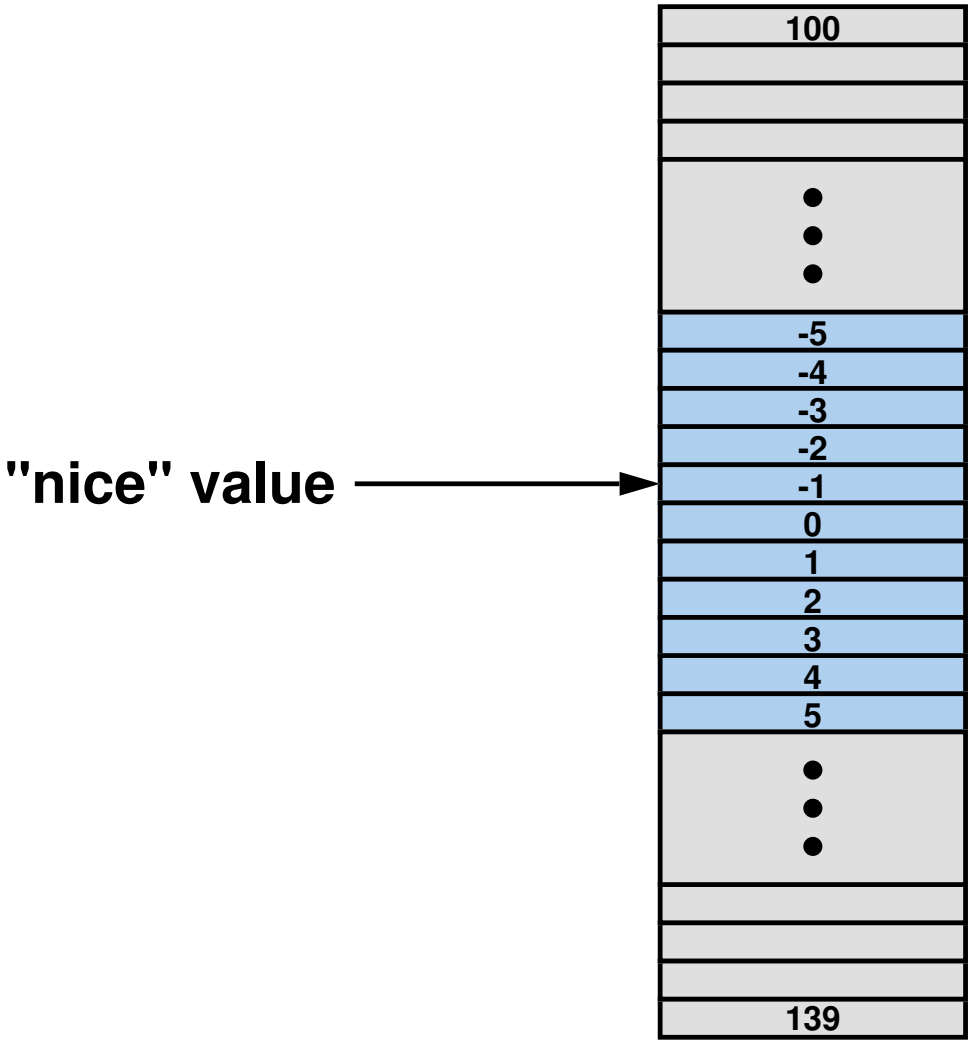


O(1) Scheduler: Queues

- Two queues per processor
  - active: processes with remaining time slice
  - expired: processes with no more time slice
  - each queue is an array of lists of processes of the same priority
    - bitmap indicates which priorities have processes
  - processors scheduled from private queues

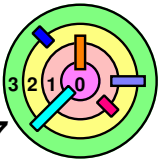


O(1) Scheduler: Priorities



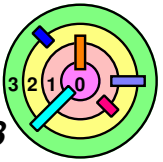
O(1) Scheduler: Actions

- Process switch
  - pick best priority from active queue
    - if empty, switch active and expired
  - new process's time slice is function of its priority
- Wake up
  - priority is boosted or dropped depending on sleep time
  - higher priority processes get longer time quanta
- Time-slice expiration
  - interactive processes rejoin active queue
    - unless processes have been on expired queue too long

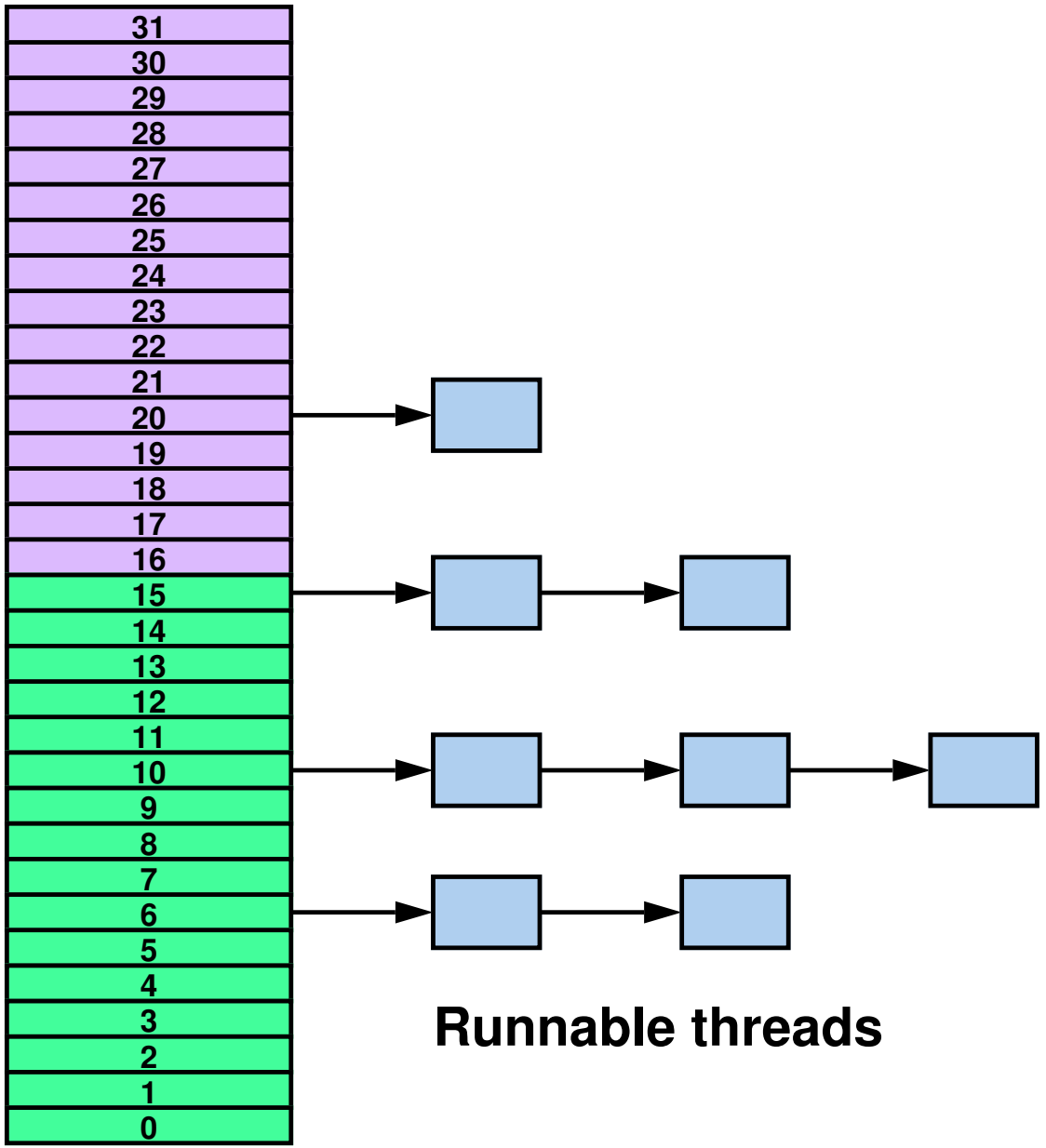


O(1) Scheduler: Load Balancing

- Processors with empty queues steal from busiest processor
  - checked every millisecond
- Processors with relatively small queues also steal from busiest processor
  - checked every 250 milliseconds

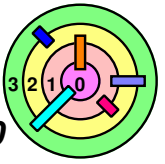


Uniprocessor Windows



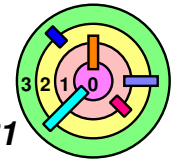
Improving Real Time

- Multimedia applications need 80% of processor time
- Make sure normal applications get at least 20%
- How?
- Windows solution: MMCSS
  - multimedia class scheduler service
  - dynamically manage multimedia threads
    - run at real-time priority 80% of time
    - run at normal priority 20% of time



Which Processor?

- Newly created thread assigned *ideal processor*
  - randomly chosen
- May also set *affinity mask*
  - may be scheduled only on processors in mask
- Scheduling decision:
  - if idle processors available
    - first preference: ideal processor
    - second preference: most recent processor
  - otherwise
    - joins run queue of ideal processor



Some Details ...