The basics of file systems

Consensus in a distributed system

Today we are going to see how to implement a reliable distributed FSM.

Reminder

The algorithm of a proposer:

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2. Send $\mathrm{prepare}(n)$ to all acceptors. It is a request to ignore requests with the epoch number $< n$.
3. Wait for $\mathrm{promise}(n, m_i, v_i)$ from a majority of acceptors and **remember a value v with the highest epoch number**. If all replies have $v_i = nil$, the proposer may propose its value.
4. Send $\mathrm{propose}(n, v)$ to all acceptors **that have replied with a promise**.
5. Wait for $\mathrm{accept}()$ from a majority of acceptors.
6. If timed out, go to #1.

The algorithm of an acceptor:

1. Upon receiving $\mathrm{prepare}(n)$, remember the epoch n and ignore all requests with lower epoch numbers. Reply with $\mathrm{promise}(n, m, v)$ where (m, v) is the last accepted value or (nil, nil) if no value has been accepted yet.
   Note: $\mathrm{promise}(n, m, v)$ has $n > m$.
2. Upon receiving $\mathrm{propose}(k, w)$ with k that is greater than the last remembered epoch, accept the value (k, w) and reply $\mathrm{accept}(k, w)$.

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Improvement: upon receiving a $\mathrm{propose}(k, w)$ with a stale epoch number k, an acceptor can reply with a NACK (Negative ACKnowledgement) to the proposer. PAXOS works fine if $\mathrm{propose}(k, w)$ is ignored and the proposer needs to time out. However, a NACK enables the proposer to restart much sooner.

Replicated FSM

From now on we will assume that every process plays all 3 PAXOS roles (proposer, acceptor and learner). Moreover, assume there is only one process proposing new values.

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1. choose a new epoch number and send prepare(),
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   - Every prepare() and promise() from a process P includes the number of the last step committed by P. This way processes can learn that a cluster member is lagging and can send it the missing tail.
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1. Suppose a process lags behind the cluster (suppose it had network problems for a while). How does it catch up?
2. How many `fsync()`s does each step need?
   - the proposer needs to persist the epoch number in order to not reuse it,
   - acceptors need to persist the epoch number to NACK requests with lower epochs,
   - acceptors need to persist a value that was proposed to them,
   - acceptors need to persist the journal length upon commit.

   Overall, we need 4 `fsync()`s that go back-to-back.

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Problem: `fsync()`s have a pronounced negative impact on the performance:

1. PAXOS runs at least 4x slower than the storage of cluster members.
2. At steps 2-5, every member must make `fsync()`s of its own which makes PAXOS vulnerable to tail latencies.

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Idea: a proposer may do steps 1 and 2 only once, and then loop through steps 3 to 6 until receiving a NACK. A NACK means that another participant decided to become the distinguished proposer and a proposer election must be repeated.

To prove the correctness, one can interpret the loop over steps 3 to 6 as a single round of PAXOS that selects a value "transitions to make in steps N_0 through N_1" where N_1 is the last round number where step 6 succeeded.

This way most appends to the journal needs only 2 `fsync()`s instead of 4.

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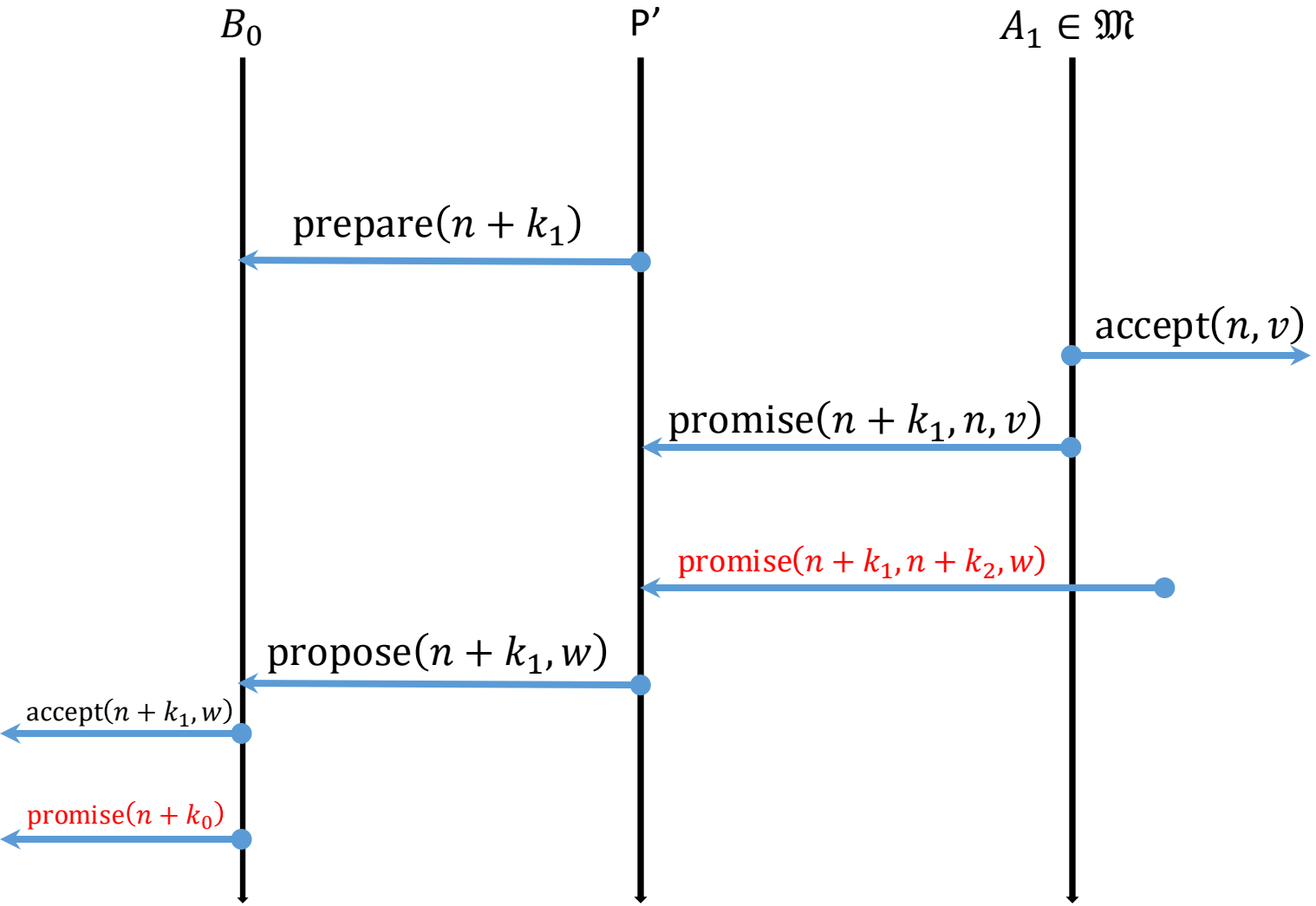
Idea: the number of `fsync()`s can be reduced further if every iteration of steps 3 to 6 processes a batch of requests instead of single requests. This is possible if a service has multiple clients, and the request queue is always deep enough.

Question: how to choose the batch sizes? – Adaptive batching.

Safety (only one value can be chosen)

It is **not** possible that a majority $\mathfrak{M}$ of acceptors accepted a value (n, v) and then some of them accepted a different value $(n + k, w)$ with $k > 0$ and $w \neq v$.



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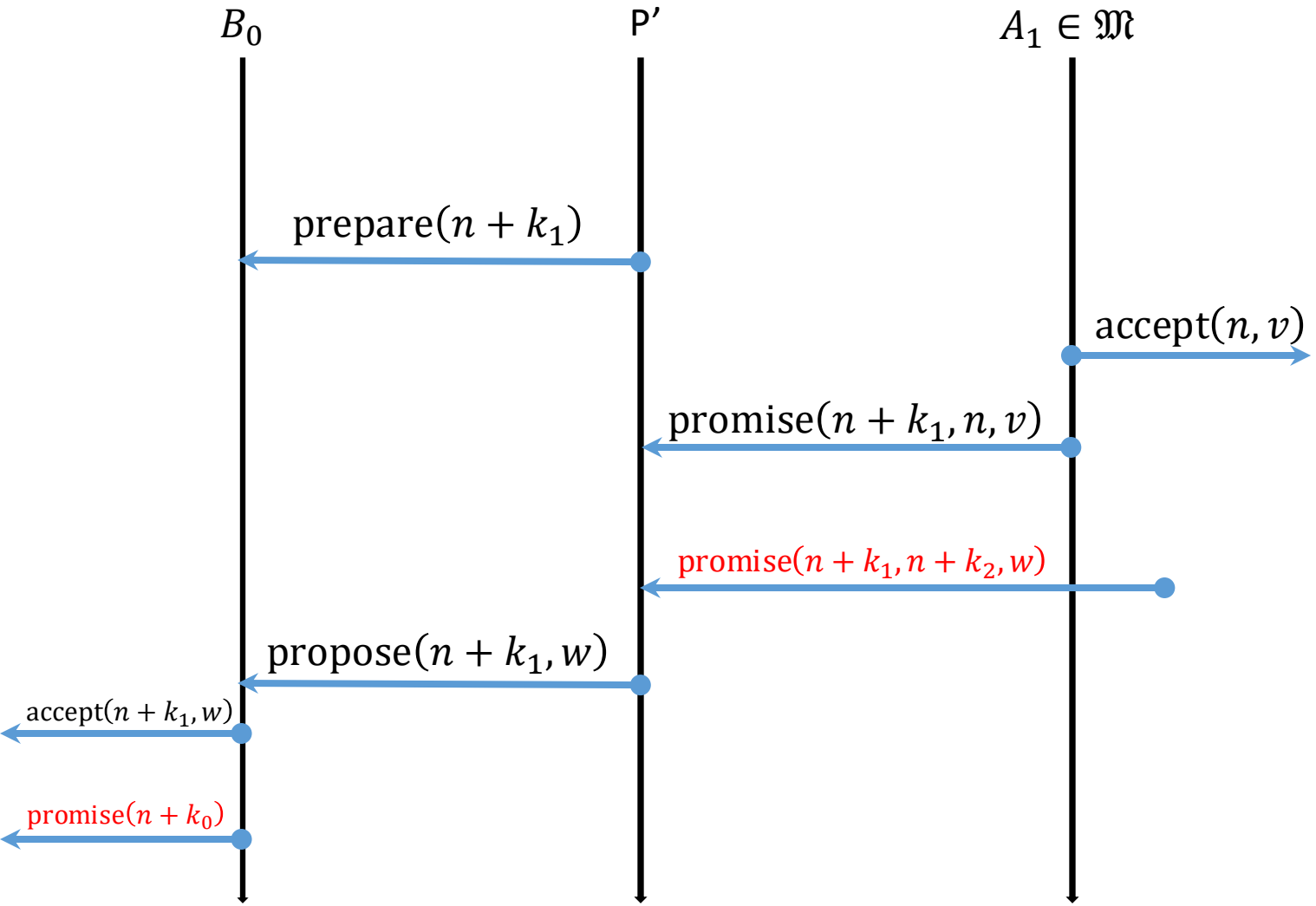

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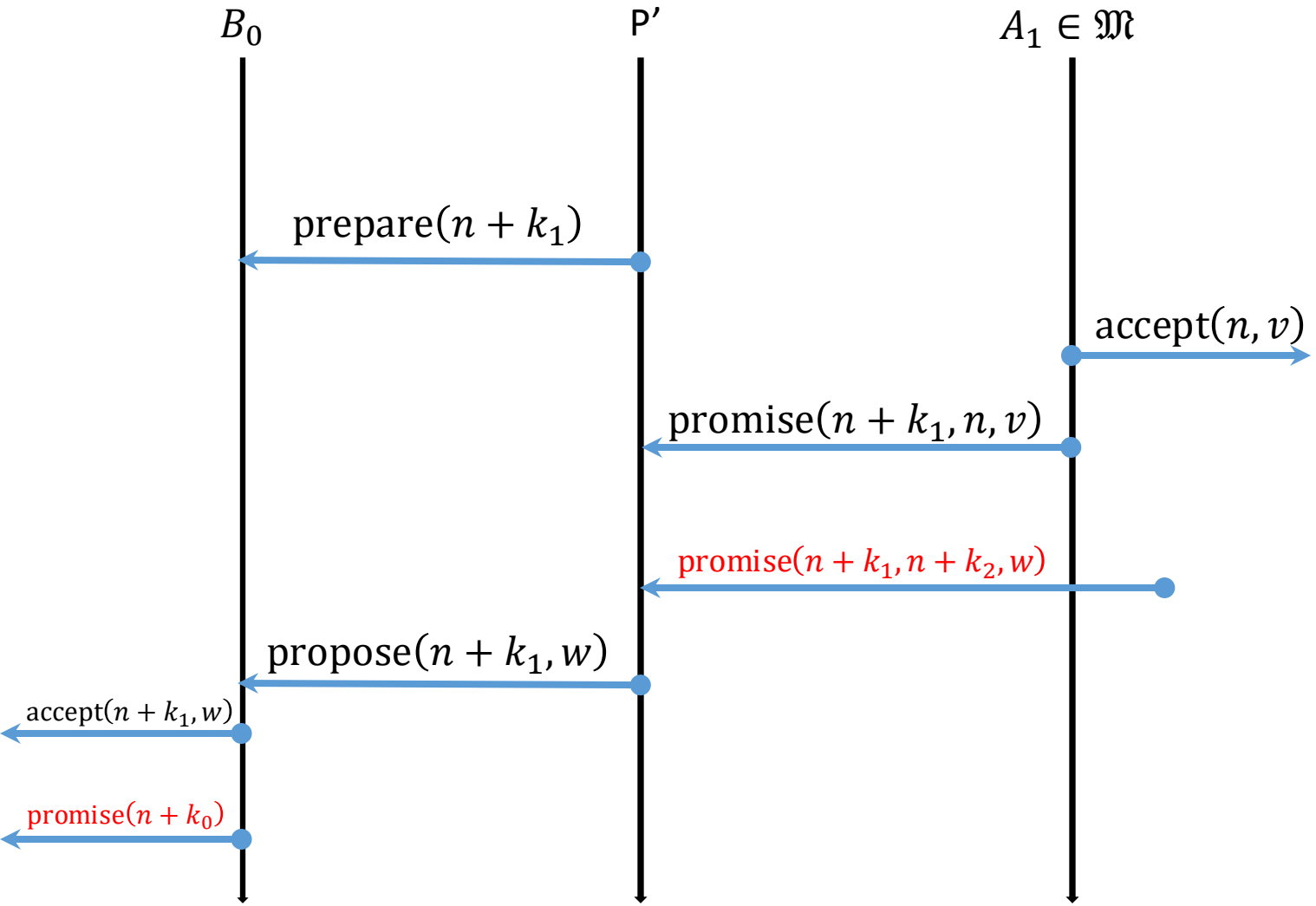

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Conversely, if it is not possible to send propose$(n + k, w), w \neq v$ to an acceptor that had already accepted v, then PAXOS chooses at most one value out of proposed values.

Generalised quorums

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We can introduce separate quorums for PAXOS phase 1 (prepare/promise) and phase 2 (propose/accept). The quorums are families of sets such that any phase 1 quorum intersects every phase 2 quorum.

This version of PAXOS is called “Flexible PAXOS”.

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Example: if a cluster has N members then we may use subsets with N-1 elements as phase 1 quorums, and subsets with 2 elements as phase 2 quorums.

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Batching + small phase 2 quorums reduce the number of `fsync()`s needed per each operation and make tail latencies less pronounced.

Still, PAXOS is not a tool to increase the throughput of a system by adding more nodes. It is a way to implement fault-tolerance. Typically, PAXOS is used to persist decisions on partitioning a system and choosing masters for subsets of data.

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More problems:

1. Making a snapshot may not block modifications of the FSM so as to introduce no latency.
2. Cluster nodes that lag behind* can no longer catch up by copying a part of the journal. They may need to copy a whole snapshot. What happens if copying a snapshot S takes too long to transfer and S is replaced with S’ during the copy?

** A cluster need not be unhealthy for some nodes to lag behind. Consider adding a new node to a cluster.*

Reminder: the failure model of PAXOS

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2. Processes may crash and restart at any moment.
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Programmable switches can modify IP packets on the fly and can order packets that arrive via different ports:

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A programmable switch can augment every IP packet with an additional header that contains a global sequence counter.

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With a programmable switch, one can implement Ordered Unreliable Multicast. It is a network operation that has the following properties:

1. If two messages m and m' are sent to a set of nodes R, then every node in R receives them in the same order (if it receives them at all).
2. If a message m is sent to a set of nodes R then either
    1. Every node in R receives the message m itself or a message "m was lost".
    2. No node in R receives m, nor "m was lost".

We can use Ordered Unreliable Multicast to send `propose()`s and `accept()`s. Thanks to OUM, all acceptors receive `propose()`s in the same order and can accept them immediately. Loss of any `propose()` or `accept()` is also detected by OUM. Process(es) that detected a message loss switch to phase 1 of PAXOS and start the re-election of the distinguished proposer.

- https://www.usenix.org/system/files/conference/osdi16/osdi16-li.pdf
  Just say NO to PAXOS overhead: replacing consensus with network ordering.

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- bit rot that may randomly corrupt the on-disk or in-memory state of nodes,
- bugs in the implementation of nodes.

It is not feasible or reasonable to prove the correctness of cluster nodes in most cases, but we can make failures rare enough:

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  - https://antithesis.com/blog/deterministic_hypervisor
- Fuzz testing, generation of random test inputs and minimisation of testcases:
  - https://go.dev/doc/security/fuzz/
  - https://www.cse.chalmers.se/edu/year/2012/course/DIT848/files/13-GL-QuickCheck.pdf
  - https://github.com/google/AFL

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- Deterministic simulation:
  - https://github.com/asatarin/testing-distributed-systems?tab=readme-ov-file#foundationdb
  - https://antithesis.com/blog/deterministic_hypervisor
- Fuzz testing, generation of random test inputs and minimisation of testcases:
  - https://go.dev/doc/security/fuzz/
  - https://www.cse.chalmers.se/edu/year/2012/course/DIT848/files/13-GL-QuickCheck.pdf
  - https://github.com/google/AFL
- Simple Testing Can Prevent Most Critical Failures: An Analysis of Production Failures in Distributed Data-Intensive Systems: https://www.usenix.org/system/files/conference/osdi14/osdi14-paper-yuan.pdf

Another example of a complex state space

```
pthread_mutex_t mtx;
pthread_cond_t cv;
...
std::deque<int> queue;
constexpr sizeLimit = ...;
...


void put(int x)
{
    pthread_mutex_lock(&mtx);

    while (queue.size() >= sizeLimit)
        pthread_cond_wait(&cv, &mtx);
    queue.push_back(x);

    pthread_cond_signal(&cv);
    pthread_mutex_unlock(&mtx);
}
```

```
int get()
{
    int x;

    pthread_mutex_lock(&mtx);

    while (queue.empty())
        pthread_cond_wait(&cv, &mtx);
    x = queue.pop_front();

    pthread_cond_signal(&cv);
    pthread_mutex_unlock(&mtx);

    return x;
}
```

The problem: implement a bounded queue that supports multiple concurrent readers and writers.

The implementation on this slide has a problem that

1. happens only when the total number of users is greater than the maximum queue depth,
2. happens rarely even if condition #1 is satisfied.

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The problem: implement a bounded queue that supports multiple concurrent readers and writers.

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2. happens rarely even if condition #1 is satisfied.

Readers are supposed to wake writers, and vice versa.

However, `pthread_cond_signal()` wakes a random sleeping thread.

A model of a bounded queue

Let us model the program from the previous slide with TLA+.

See: Specifying systems, https://lamport.azurewebsites.net/tla/book-02-08-08.pdf.

We will use TLA+ Model Checker that walks the state space of a model and verifies whether or not a predicate holds in all states. It can do both breadth-first search and randomised depth-first search. Breadth-first search is exhaustive and yields shortest paths to states that invalidate a predicate. Depth-first search can explore parts of state spaces that are too big.

A model of a bounded queue

Let us model the program from the previous slide with TLA+.

See: Specifying systems, https://lamport.azurewebsites.net/tla/book-02-08-08.pdf.

We will proceed this way:

1. Declare tunable parameters of the model. Typically, these are parameters like the number of participant processes, the maximum capacity of queues, etc.
2. Declare variables that describe the state. Unlike tunables from #1, variables change upon every state transition.
3. Declare predicates that hold at every state of the model.
4. Declare a predicate that defines the initial state.
5. Declare predicates that hold iff the model makes a specific state transition. Examples: “A sends a message to B”, ”B receives a message from A”, “a message is lost”, etc.
6. Construct a formula to express “the system starts at the initial state and makes a state transition at every step”.
7. Declare predicates that we expect to follow from the rules 3-5.
8. Have TLC search the state space for counterexamples to #7.

A model of a bounded queue

TLA+ code

```
CONSTANT BufferCapacity
CONSTANTS Readers, Writers
```

LaTeX-formatted

First, let us list constants that define the properties of our system:

- the maximum queue depth,
- the sets of readers and writers.

A model of a bounded queue

TLA+ code

```
ASSUME Readers /= {}
ASSUME Writers /= {}
ASSUME (BufferCapacity \in Nat) /\ (BufferCapacity > 0)
```

LaTeX-formatted

$$\begin{aligned}&\text{ASSUME } Readers \neq \{\}\\&\text{ASSUME } Writers \neq \{\}\\&\text{ASSUME } (BufferCapacity \in Nat) \land (BufferCapacity > 0)\end{aligned}$$

- {} is the empty set,
- /= means “not equal”,
- /\ and \/ are logical “and” and “or”, respectively.

A model of a bounded queue

TLA+ code

```
VARIABLES bufferLen, threadStates
```

LaTeX-formatted

This declares variables that define the state of the system. The state space explored by TLC is the set of all possible values of these variables.

These declarations place no constraints on values of the variables. They may be arbitrary sets.

A model of a bounded queue

TLA+ code

```
Threads == Readers \cup Writers

(* "R" is for Running,
   "M" is "owns Mutex and running",
   "S" is for Sleeping *)

ThreadState == {"R", "M", "S"}

threadStates_TypeInvariant ==
  threadStates \in [Threads -> ThreadState]
```

LaTeX-formatted

$$Threads \triangleq Readers \cup Writers$$

$$ThreadState \triangleq \{\text{“R”}, \text{“M”}, \text{“S”}\}$$
$$threadStates\_TypeInvariant \triangleq threadStates \in [Threads \to ThreadState]$$

`threadStates_TypeInvariant` is a predicate which is true iff `treadStates` is a map from the set of threads to the set of thread states.

At a later stage we will require `threadStates_TypeInvariant` to be true in every state of our model.

- == means “by definition”,
- {A, B, …} defines a set by listing its elements,
- [X -> Y] is the set of maps from X to Y.

A model of a bounded queue

TLA+ code

```
Init ==
  /\ bufferLen = 0
  /\ threadStates_TypeInvariant
  /\ \A t \in Threads: threadStates[t] = "R"
```

LaTeX-formatted

$$
\begin{aligned}
&Init \triangleq \\
&\land\ bufferLen = 0 \\
&\land\ threadStates\_TypeInvariant \\
&\land\ \forall\, t \in Threads : threadStates[t] = \text{“R”}
\end{aligned}
$$

This is a predicate that is true iff the model is in its initial state: the buffer is empty and all threads are runnable.

A model of a bounded queue

TLA+ code

```
(* t acquires the mutex *)
AcquireLock(t) ==
  /\ threadStates[t] = "R"
  /\ \forall ta \in Threads: threadStates[ta] /= "M"
  /\ threadStates' = [threadStates EXCEPT ![t] = "M"]
  /\ UNCHANGED bufferLen
```

LaTeX-formatted

$$
\begin{aligned}
&AcquireLock(t) \triangleq \\
&\land\ threadStates[t] = \text{“R”} \\
&\land\ \forall\, ta \in Threads : threadStates[ta] \neq \text{“M”} \\
&\land\ threadStates' = [threadStates \text{ EXCEPT } ![t] = \text{“M”}] \\
&\land\ \text{UNCHANGED } bufferLen
\end{aligned}
$$

Predicates that describe state transitions do so by placing constraints on the current state and the next possible state.

The predicate `AcquireLock(t)` is true iff thread t acquires the mutex at the current state transition.

- F[t] is the value of map F at t,
- x and x’ denote the values of x in the current state and in the next state, respectively,
- UNCHANGED <<x, y, …>> is a shorthand for x’ = x /\ y’ = y /\ …

A model of a bounded queue

TLA+ code

```
ReadBlock(t) ==
  /\ t \in Readers
  /\ threadStates[t] = "M"
  /\ bufferLen = 0
  /\ threadStates' = [threadStates EXCEPT ![t] = "S"]
  /\ UNCHANGED bufferLen
```

LaTeX-formatted

$$
\begin{aligned}
&ReadBlock(t) \triangleq \\
&\land\ t \in Readers \\
&\land\ threadStates[t] = \text{“M”} \\
&\land\ bufferLen = 0 \\
&\land\ threadStates' = [threadStates \text{ EXCEPT } ![t] = \text{“S”}] \\
&\land\ \text{UNCHANGED } bufferLen
\end{aligned}
$$

`ReadBlock(t)` is true iff thread t attempted to read from the queue, detected that the queue was empty, and blocked. After this transition t sleeps in `pthread_condvar_wait()`.

Note that this transition is only possible if the current thread owns the mutex: `threadStates[t] = “M”`.

A model of a bounded queue

TLA+ code

```
ReadOk(t) ==
  /\ t \in Readers
  /\ threadStates[t] = "M"
  /\ bufferLen > 0
  /\ bufferLen' = bufferLen - 1
  /\ UnlockAndWakeOne(t)
```

LaTeX-formatted

$$
\begin{aligned}
&ReadOk(t) \triangleq \\
&\land\ t \in Readers \\
&\land\ threadStates[t] = \text{“M”} \\
&\land\ bufferLen > 0 \\
&\land\ bufferLen' = bufferLen - 1 \\
&\land\ UnlockAndWakeOne(t)
\end{aligned}
$$

`ReadOk(t)` is true iff thread t read a value from the queue, unlocked the mutex and (possibly) woke another sleeping thread. We will declare `UnlockAndWakeOne(t)` later.

A model of a bounded queue

TLA+ code

```
UnlockAndWakeOne(self) ==
LET
 sleepingThreads == {t \in Threads: threadStates[t] = "S"}
IN
 IF sleepingThreads = {}
 THEN
  threadStates' = [threadStates EXCEPT ![self] = "R"]
 ELSE
  \E t \in sleepingThreads:
  threadStates' = [threadStates EXCEPT ![self] = "R", ![t] = "R"]
```

LaTeX-formatted

$$
\begin{array}{l}
UnlockAndWakeOne(self) \triangleq \\
\text{LET} \\
sleepingThreads \triangleq \{t \in Threads : threadStates[t] = \text{“S”}\} \\
\text{IN} \\
\text{IF } sleepingThreads = \{\} \\
\ \text{THEN} \\
threadStates' = [threadStates \text{ EXCEPT } ![self] = \text{“R”}] \\
\ \text{ELSE} \\
\exists\, t \in sleepingThreads : \\
threadStates' = [threadStates \text{ EXCEPT } ![self] = \text{“R”}, ![t] = \text{“R”}]
\end{array}
$$

A model of a bounded queue

TLA+ code

```
Next == \E t \in Threads:
  \/ AcquireLock(t)
  \/ WriteOk(t)
  \/ WriteBlock(t)
  \/ ReadOk(t)
  \/ ReadBlock(t)
```

LaTeX-formatted

$$
\begin{aligned}
&Next \triangleq \exists\, t \in Threads : \\
&\lor\ AcquireLock(t) \\
&\lor\ WriteOk(t) \\
&\lor\ WriteBlock(t) \\
&\lor\ ReadOk(t) \\
&\lor\ ReadBlock(t)
\end{aligned}
$$

This predicate is true iff the system made a state transition. A state transition may be one of the following actions:

- a thread acquires a mutex,
- a thread attempted to write a value and succeeded, or blocked,
- a thread attempted to read a value and succeeded, or blocked.

A model of a bounded queue

TLA+ code

```
Spec == Init /\ [][Next]_<<bufferLen, threadStates>>
```

LaTeX-formatted

$$Spec \triangleq Init \land \Box[Next]_{\langle bufferLen,\, threadStates \rangle}$$

This is the definition of our model: `Init` is true in the initial state and `Next` is true at every state transition.

- []E is true iff E is true at every state transition.

A model of a bounded queue

TLA+ code

```
AtMostOneMutexOwner ==
 LET owners == {t \in Threads: threadStates[t] = "M"}
 IN Cardinality(owners) <= 1

Liveness ==
 LET
 runnable == {t \in Threads: threadStates[t] \in {"R", "M"}}
 IN runnable /= {}
```

LaTeX-formatted

$$AtMostOneMutexOwner \triangleq$$
$$\text{LET } owners \triangleq \{t \in Threads : threadStates[t] = \text{“M”}\}$$
$$\text{IN } \quad Cardinality(owners) \leq 1$$

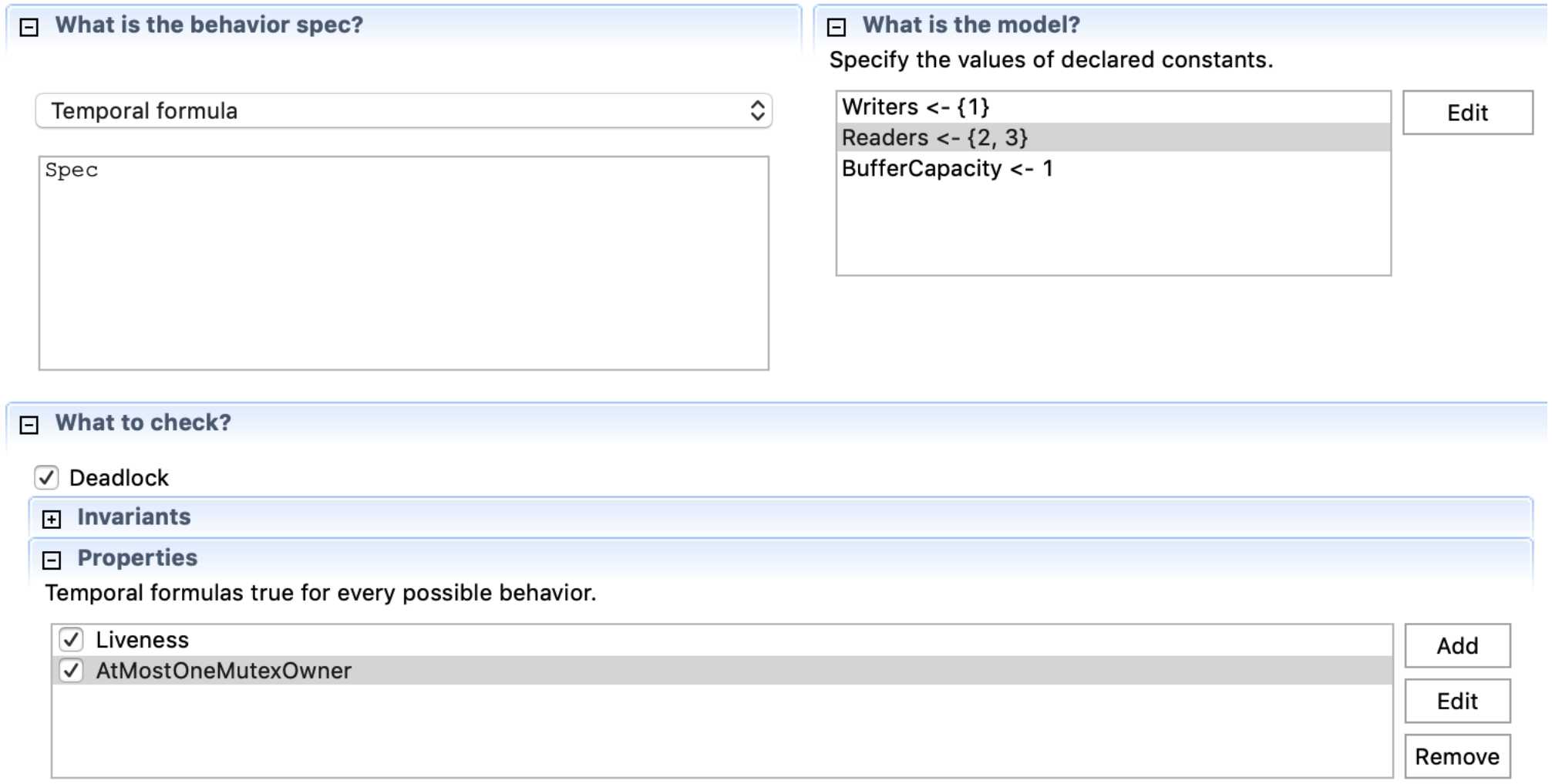
$$Liveness \triangleq$$
$$\text{LET } runnable \triangleq \{t \in Threads : threadStates[t] \in \{\text{“R”}, \text{“M”}\}\}$$
$$\text{IN } \quad runnable \neq \{\}$$

Now let us define predicates that describe desired properties of our model:

- at most one thread owns the mutex,
- there is at least one runnable thread.

A model of a bounded queue

Now let us have TLA+ Model Checker walk the states of our model:



A model of a bounded queue

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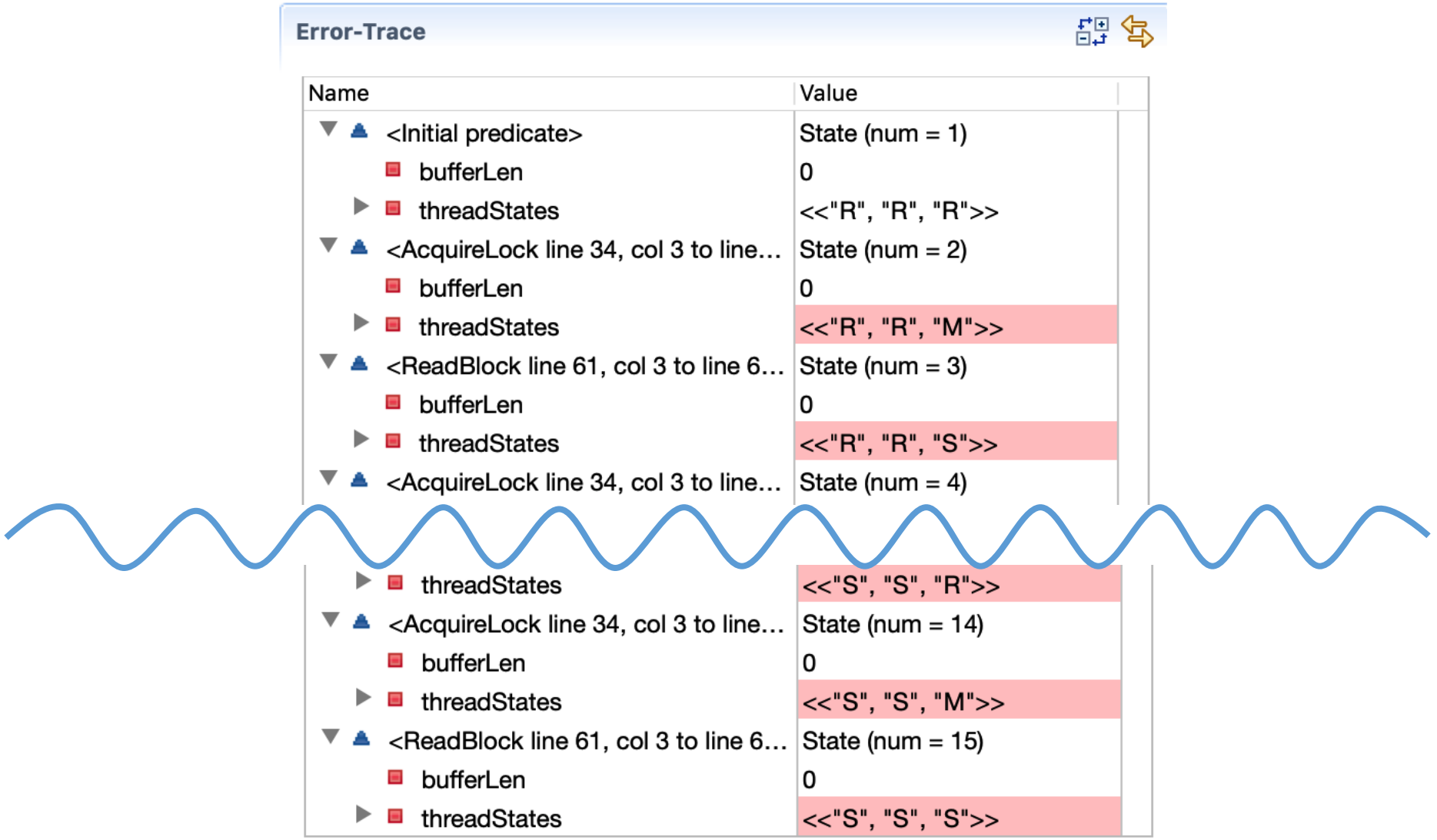

To do at home

Use TLC to find a way to transport a goat, a wolf, and a cabbage from one shore of a river to the other one.

Idea:

1. Declare predicates that describe the rules of transporting,
2. Declare a predicate “the goat, the wolf and the cabbage are not on the other shore”.
3. Use TLC to find a counterexample to #2.

To read

1. Specifying systems, https://lamport.azurewebsites.net/tla/book-02-08-08.pdf.
2. TLA+ Toolbox https://lamport.azurewebsites.net/tla/toolbox.html.