PURDUE UNIVERSITY

Principles of Concurrency

Week 3

Simple Concurrent Data Structures

Material adapted from Herlihy and Shavit, Art of Multiprocessor Programming, Chapters 9 and 10

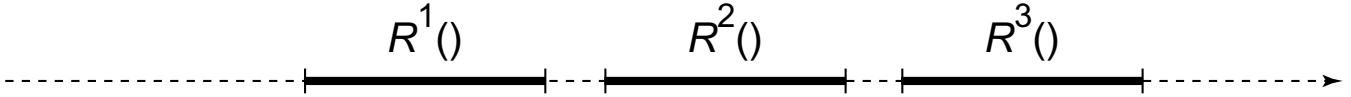
Shared Concurrent Objects

- Desirable properties of a concurrent object:
  - safety: accesses to these object should obey desired consistency properties
  - liveness: all threads should be able to eventually access an object if they wish to do so
- Simplest kind of object:
  - read-write register (name is a historical artifact)
- An object is said to be *wait-free* if:
  - every method defined by its implementation is guaranteed to complete in a finite number of steps regardless of the number of other concurrent calls to the method made by other threads
  - Guarantees progress without appealing to a scheduler implementation

Atomic Register

- A single-writer, multi-reader (SWMR) register implementation:
  - is *safe* if it ensures that a read() operation not overlapping with a write() operation returns the value of the most recently completed write() in a trace.

    It provides no guarantees when operations overlap.
  - is regular if it is safe but its writes are not atomic
    - readers can observe the write happening, "flickering" between old and new values



- A multi-writer, multi-reader (MWMR) register implementation:
  - is atomic if is *atomic* if it guarantees that every read() returns the value of the most recently completed write().

Suppose $R^1()$ returns 0. What can R^2 and R^3 return in a safe register? atomic register? regular register?

Histories

- A history is a trace of operations on an object
- Every read() call in a history must return the value written by some previously executed write()
  - no "out-of-thin-air" values
- A history can include method invocation and response events
  - A method call in a history is defined by the interval containing the method invocation and its response
  - The set of method calls in a history defines a partial order over the happens-before relation. Why is this not total?
- A register implementation defines a total order on writes
  - This is sometimes known as coherence

Properties

- A regular register does not allow reads to:
  - witness writes from the future in a history
  - witness a write that has been overwritten by another visible write
- An atomic register additionally mandates that an earlier read cannot return a value later than that returned by a later read

$$\text{if} \quad R^i \rightarrow R^j \quad \text{then} \quad i \leqslant j. \quad (*)$$

the superscripts indicate the index of the write in the history that the read observes

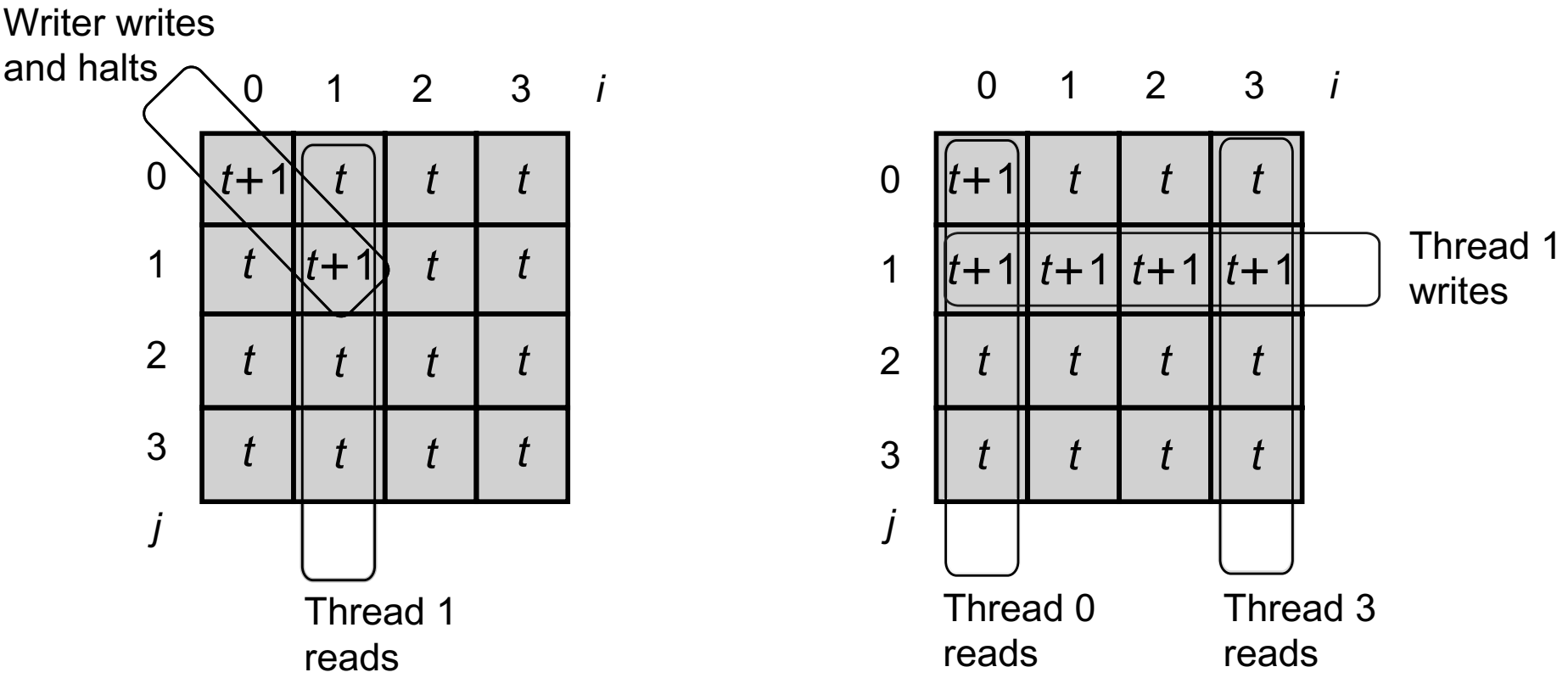
Constructions

- Can build safe MRSW registers from safe SRSW registers
  - Maintain an array of SRSW registers
  - Writes update every element in the array (non-atomically)
  - Reads guaranteed to see latest non-overlapping write
- Can build atomic SRSW registers from regular SRSW registers
  - An SRSW register has no concurrent reads
  - Requirement that write order is reflected by reads in an atomic register can be violated by a regular register if:
    - two reads overlap the same write and read values out-of-order
  - Prevent this condition from happening by using timestamps that order write calls
    - Each read remembers latest (highest timestamp) value pair read
    - A read that reads a lower value than a previous read simply ignores it
    - Interesting challenge: need to read both timestamp and value atomically
      - E.g., store both in a single 64bit word

Constructions

- Can build an atomic MRSW register from an atomic SRSW register
  - As with the construction of safe MRMW registers from safe SRSW registers, use a table of atomic SRSW registers
  - writes update table in increasing order; use a "helping" mechanism: earlier readers inform later readers of the values they've read
  - importantly, this does *not* provide MRMW capability
- Can build an atomic MRMW register from atomic MRSW registers
  - To write to the register, first read all the elements in the table and choose a timestamp higher than any observed and use that to write to the appropriate slot in the array
  - To read, first read all the elements and return the element with the highest stamp (like the Bakery algorithm)
  - Break ties using thread ids

An MRSW Atomic Register



Other kinds of locks …

- Why are approaches like Peterson's or the Bakery algorithm not sufficient:
  - cost in space and time
  - unexpected interactions with compiler optimizations
  - strong assumptions on multiprocessor hardware behavior
    - all writes are sequentially consistent, i.e., program behaves as a sequential interleaving of concurrent actions
- Consider lower-level approaches that are closer to features supported by the architecture
  - robust to compiler optimizations and underlying hardware
  - implemented as part of the processor's ISA

Test-and-Set

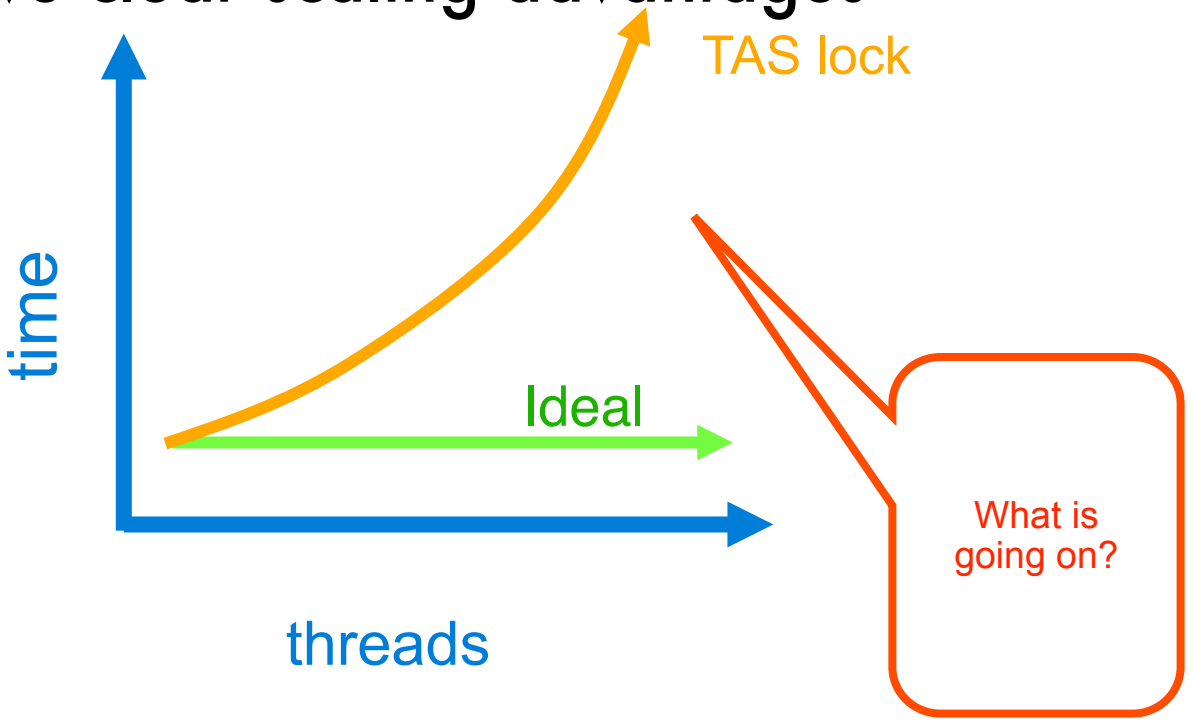

```
value : Boolean

fun getAndSet (newVal : Boolean) = {
    prior = value
    value = newVal
    return prior
}
```

- `value` represents a lock
- When `getAndSet()` returns false, the lock is free
- When `getAndSet()` returns true, the lock is held
- Acquire a lock by calling getAndSet() until it returns true
- Release lock by calling `getAndSet` with false

Test-and-set

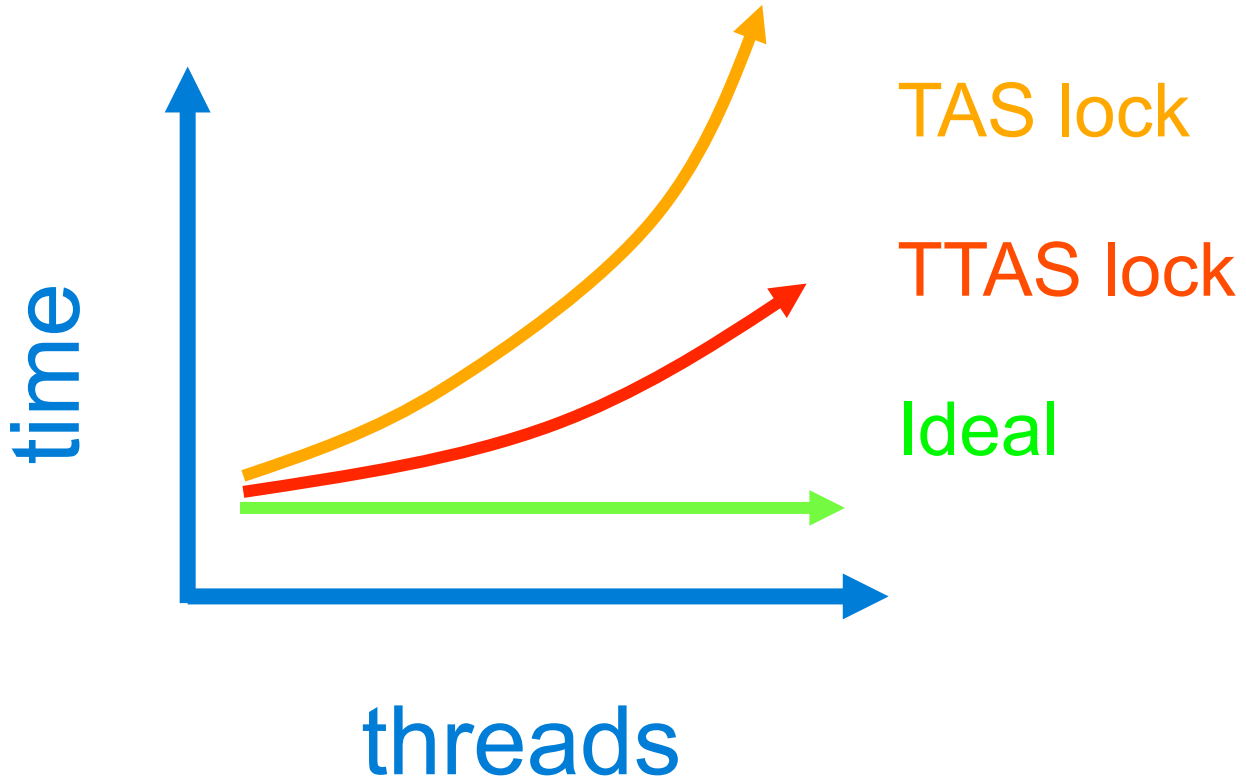
- Compared with Peterson's, this lock has a small (O(1)) footprint (compared with O(n) for Peterson or Bakery)
- Key difference:
  - It relies on an atomic Read-Modify-Write (RMW) instruction
- Should have clear scaling advantages



Test-and-Test-and-Set Lock

- Variant of test-and-set that repeatedly loops waiting for the lock to become free before trying to acquire it:

```
fun acquire() = {
   while (true) {
      while (value == true) {}
      if (!getAndSet(true)) { return }
   }
```



Compare-and-Swap

Three operands:

- a memory location (v)
- an expected value (old)
- a new value (new)

Atomically update v with new if its value is old, and return old

Use this for synchronization:

- read value A from v
- perform some computation to derive new value B
- use CAS to write B back to V

Lock-free counter:

```
val oldVal = counter.val
while (counter.CAS (oldVal, oldVal + 1) != oldVal))
    oldVal = counter.val
return counter.val
```

Taxonomy

- An algorithm is said to be *wait-free* if every thread makes process in the face of arbitrary delay (or even failure) of other threads

- An algorithm is said to be *lock-free* if some thread always makes progress
  - starvation possible

- An algorithm is said to be *obstruction-free* if at every point in the program's execution, there exists some thread that if executed in isolation for a bounded number of steps will complete