Consistency in Distributed Systems

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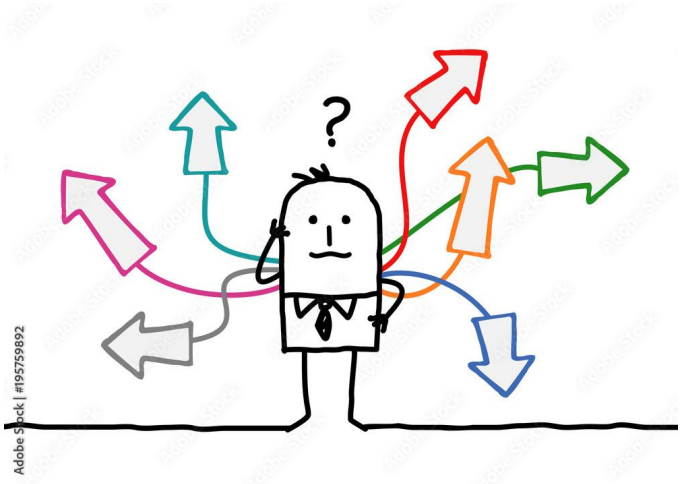
Plan

- Distributed shared data structures
- Safety properties and progress conditions
- Strong consistency (linearizability and sequential consistency)
- Weak consistency
- Progress conditions
- Conclusion

Distributed Computation

- Processes and concurrency
  - Processes may interact directly through share data structures if there is a shared memory
  - Or through messages exchanged by the different processes



Distributed shared data structures

- The basic operations are read/write on registers and possibly special instructions (C&S, T&S, ...)
- or, send/receive of messages through a communication network
- However shared data structures used by distributed applications may be more sophisticated: stacks, queues, sets, logs, graphs, etc.
- These data structures are not offered natively by processors
- Each operation on a shared data structure corresponds to a code (a function) that can be complex

Distributed shared data structures

- The push operation in Trieber/IBM's Stack (from D. Hendler)

```
Push(int v, Stack S)
1.   n := new NODE ;create node for new stack item
2.   n.val := v          ;write item value
3.   do forever         ;repeat until success
4.     node top := S.top
5.     n.next := top        ;next points to current top (LIFO order)
6.     if compare&swap(S, top, n) ; try to add new item
7.        return                    ; return if succeeded
8.   end do
```

Distributed shared data structures

- The enqueue operation in Mickael & Scott's Queue (from D. Hendler)

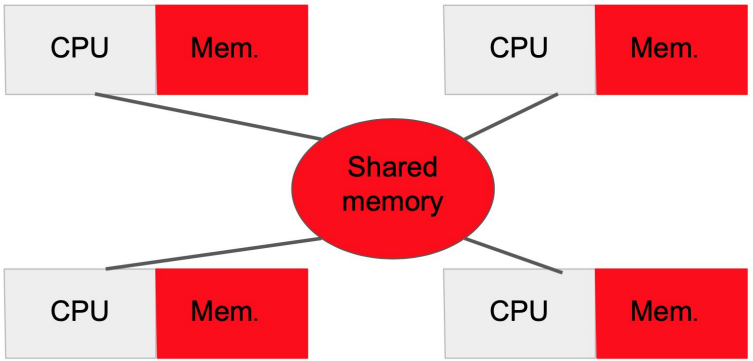
```
public boolean enq(T value) {
  Node node=new Node(value);
  while (true) {
    Node last = tail.get();
    Node next = last.next.get();
    if (last == tail.get()) {
       if (next == null) {
           if (last.next.compareAndSet(null,node) {
               tail.compareAndSet(last,node);
               return;
           }
        } else {
           tail.compareAndSet(last,next);
        }
      }
  }
}
```

Distributed Shared Data Structures

The ABD simulation (Attiya, Bar-Noy and Dolev 1995)

- It has been proved in 1995 that a shared memory (shared registers) can be emulated over a distributed system provided that there is a majority of processes that do not crash

However special instructions cannot be implemented on a message-passing system prone to process crashes



Consistency and Progress Conditions

- A data structure is defined by two properties:
  - A safety property
  - A progress condition
- Safety: It questions the meaningfulness of the results returned by operations on shared objects
- Progress: will there be a returned value and when?

Consistency and Progress Conditions

Safety properties

Ideally: The best consistency for an implemented shared object is the one that makes it indistinguishable from a physical object accessed concurrently

- One simple way to guarantee this property is to use locks: atomicity
  - Locks do not tolerate process crashes
  - 52% of bugs in Java concern the misuse of "synchronized"
  - false conflicts

- Otherwise
  - complex implementation of data structures
  - memory consuming

Consistency and Progress Conditions

Progress conditions

Ideally: Each operation terminates whatever is the behavior of the other processes (contention, order, etc.)

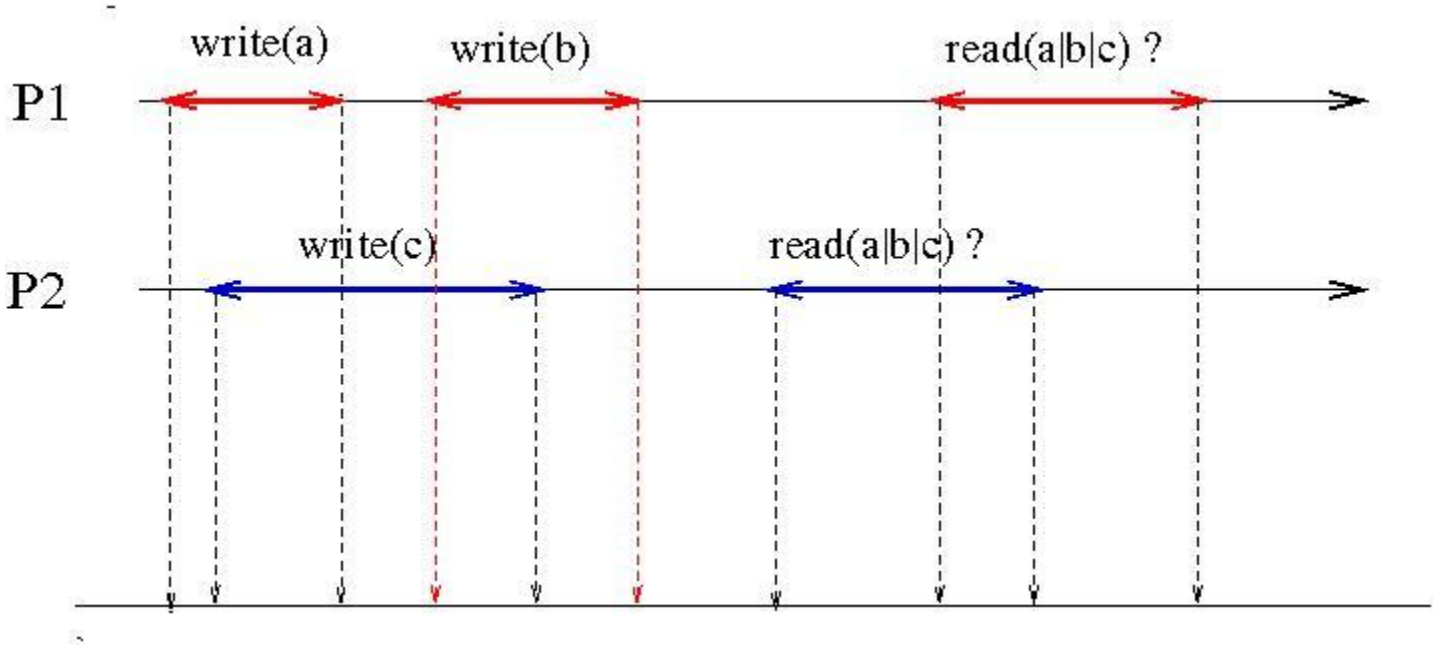
- If one uses locks there are three progress conditions
  - deadlock-free (global progress)
  - starvation-free (local progress)
  - fifo
- Otherwise
  - wait-free (local progress)
  - lock-free (global progress)
  - obstruction-free (conditional progress - no contention)

Strong Consistency (linearizability and sequential consistency)

- Linearizability and sequential consistency are usually called strong consistency
- A process cannot distinguish a strongly consistent implementation of a data structure with a physical data structure accesses concurrently
  - Wait-free linearizable shared data structures are desirable but sometimes complex or inefficient
  - Lock-free implementations may enjoy enough strong progress and acceptable complexity

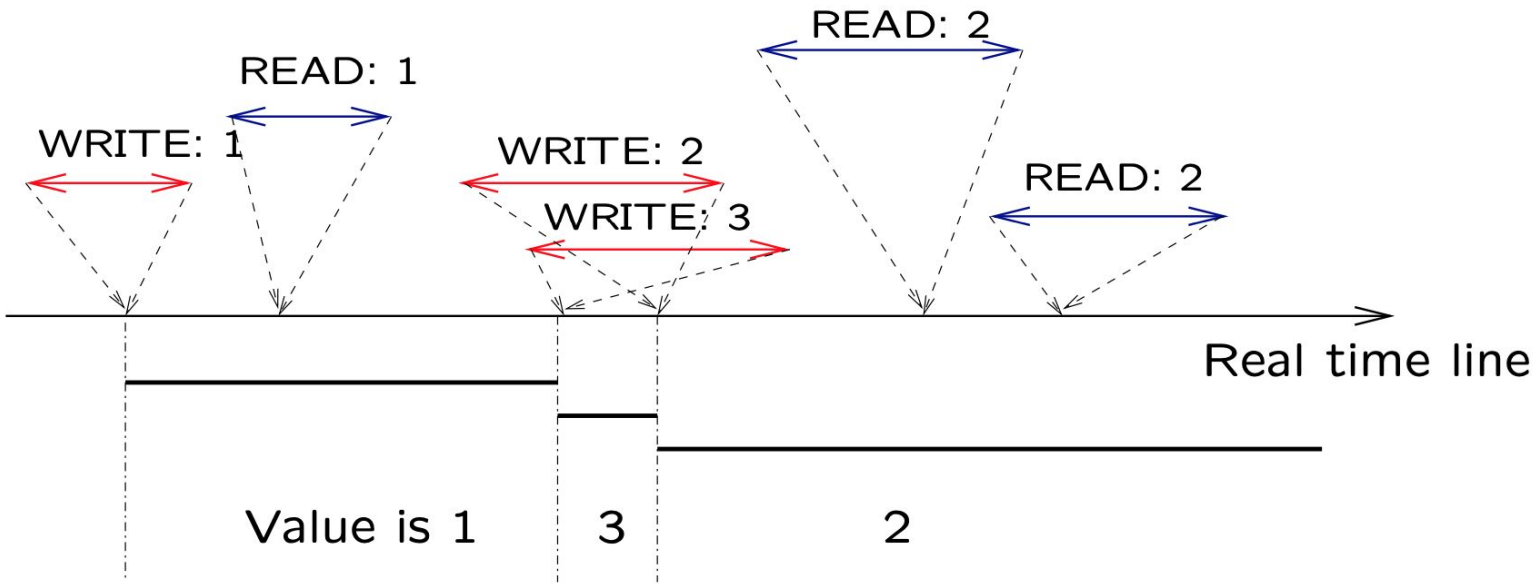
Strong Consistency (linearizability and sequential consistency)

- Linearizability (from M. Raynal)



Strong Consistency (linearizability and sequential consistency)

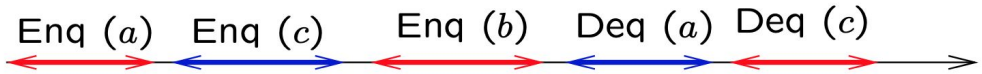
- Linearizability: a possible linearization



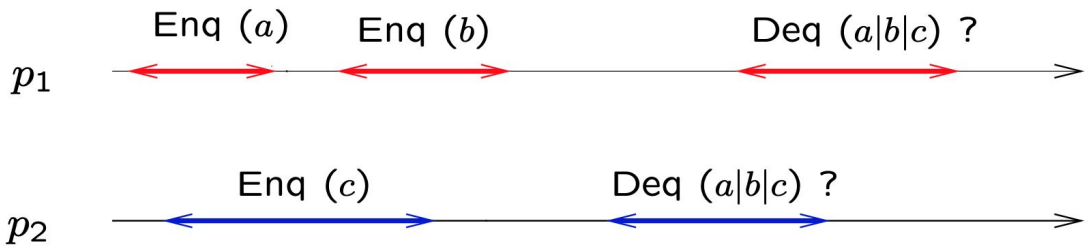
Strong Consistency (linearizability and sequential consistency)

- Linearizability: a shared queue

SEQUENTIAL:

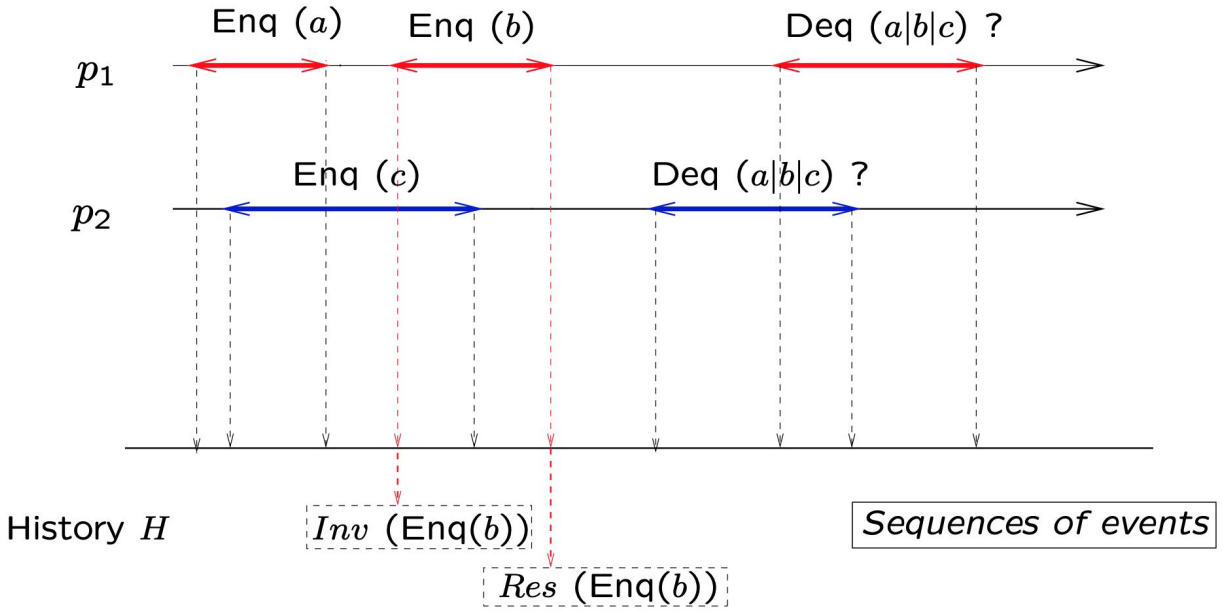


CONCURRENT:



Strong Consistency (linearizability and sequential consistency)

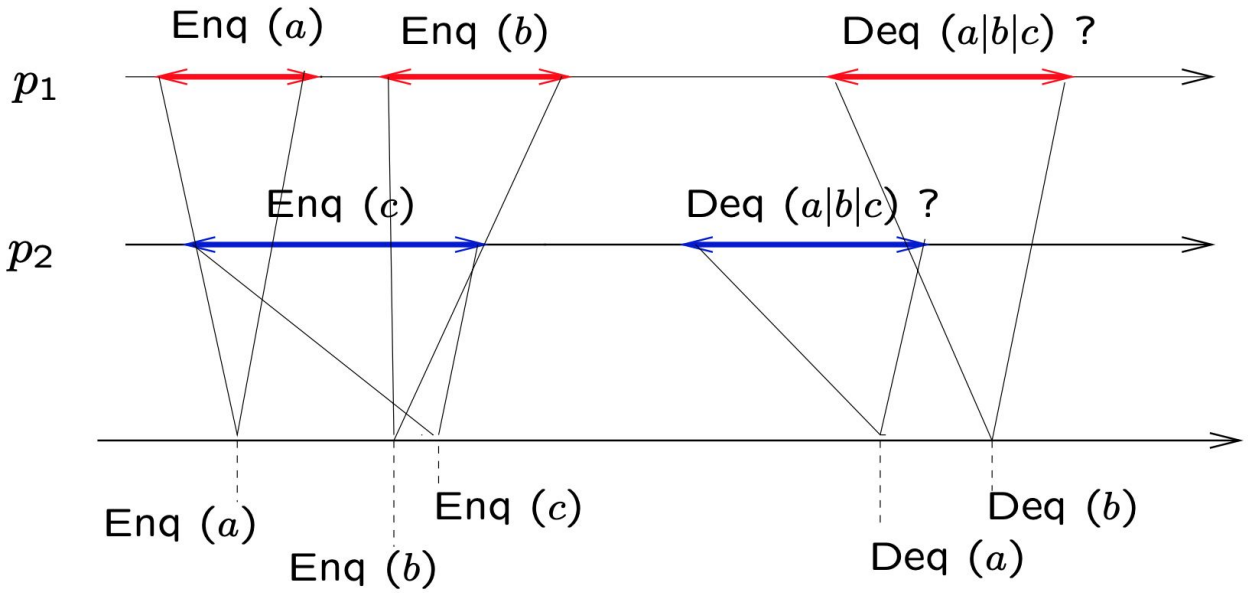
- Linearizability



A history defines a partial order on the operations

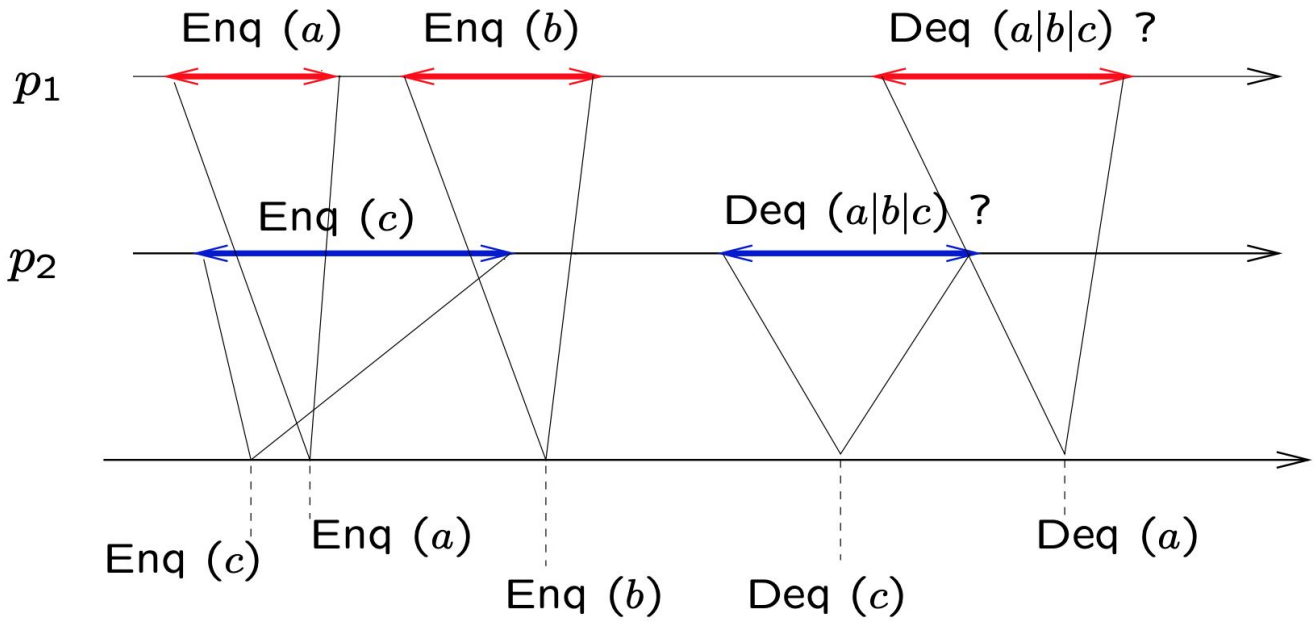
Strong Consistency (linearizability and sequential consistency)

- Linearizability



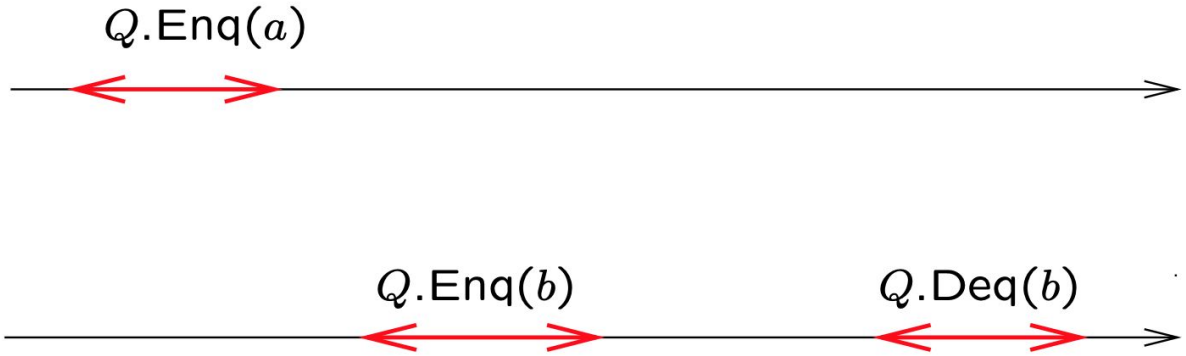
Strong Consistency (linearizability and sequential consistency)

- Linearizability



Strong Consistency (linearizability and sequential consistency)

- Sequential consistency

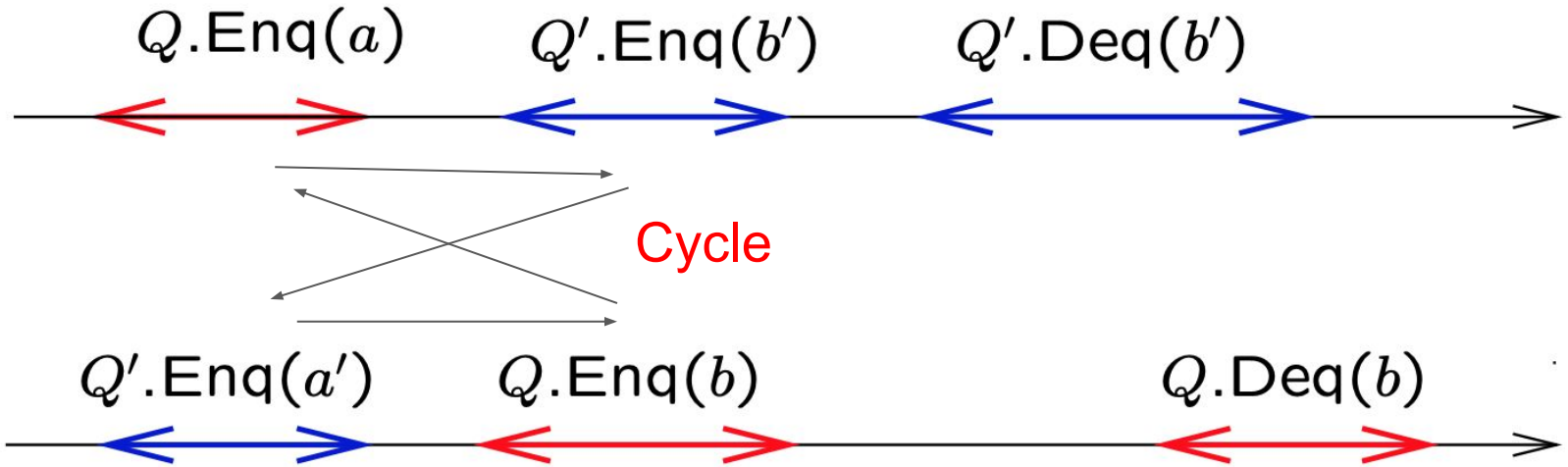


A "witness" seq history:

Q.Enq(b) Q.Enq(a) Q.Deq(b)

Strong Consistency (linearizability and sequential consistency)

- Sequential consistency: unfortunately, it does not compose!



Strong Consistency (linearizability and sequential consistency)

- Linearizability and sequential consistency cannot be distinguished in an asynchronous system
- Sequential consistency is “cheaper” than linearizability
- However, linearizability is a local property: if all objects are linearizable, then the whole computation is linearizable!
- A distribution computation is a partial order of events.
- A good consistency criterion consists in totally ordering all events
  - linearizability: total order on all events + causality + real-time order
  - sequential consistency: total order on all events + causality

Weak Consistency

- Strong consistency is usually costly in time and space
- In message-passing systems strong consistency is usually not possible and when it is possible, operation has to last the latency of the communication network:
  CAP Theorem (Consistency - Availability - Partition) Gilbert&Lynch 2002
- Attiya & Welch proved in 1994 that, when possible, strong consistency needs an operation duration proportional with network latency
- This is practically impossible for many applications such as instant messaging, collaborative editors, etc.
- In those situations, one can use weak consistency conditions:
  - ~~Cache coherence~~
  - Causal consistency
  - Eventual consistency
  - PRAM consistency
  - Serializability ...

Weak Consistency

Weak consistency conditions let each process built its own total order

- Strong eventual consistency: same total order on all update operations
- Serializability (transactions in databases): not all operations terminate
- Causal consistency: all local linearization respect causal order
- PRAM consistency: local and fifo order

There is no total order on the strength of the different consistency conditions
=> which the strongest weak consistency condition ?

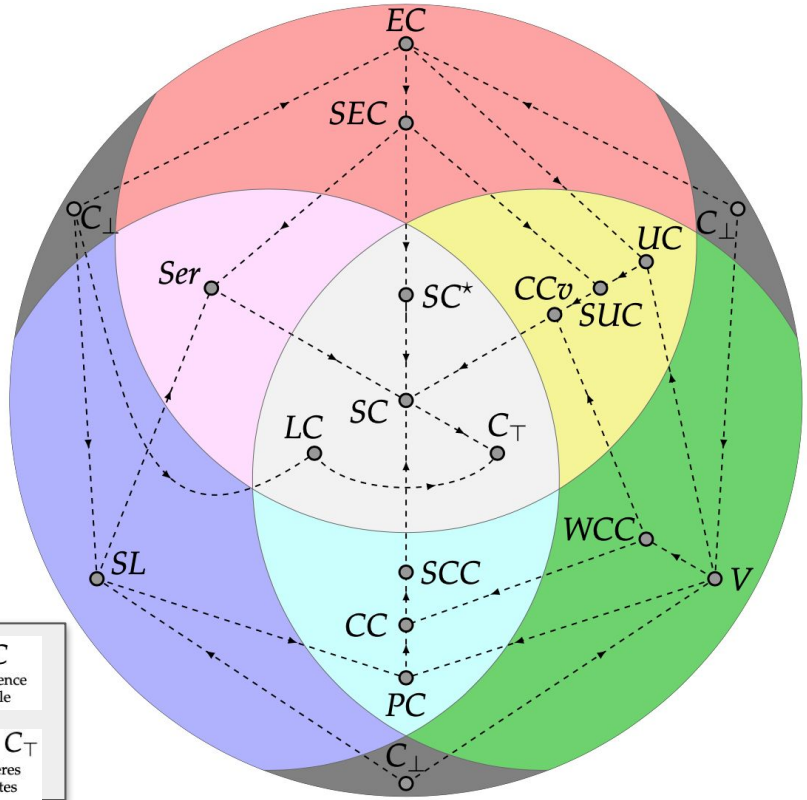
Weak Consistency

The world of consistency conditions (from M. Perrin PhD thesis)

There are 3 basic families of consistency conditions

A consistency condition that merges all of the three families falls into strong consistency

SC Cohérence séquentielle	*PC* Cohérence pipeline	*SEC* Convergence forte	*SUC* Cohérence d'écritures forte	*CCv* Convergence causale	*WCC* Cohérence causale faible	*SCC* Cohérence causale forte	*LC* Cohérence locale
*SC** Cohérence de cache	*SL* Localité d'état	*EC* Convergence	*UC* Cohérence d'écritures	*Ser* Sérialisabilité	*V* Validité	*CC* Cohérence causale	$C_\perp$ $C_\top$ Critères limites



Weak Consistency

Weak consistency for which usage

- Serialisability: substitute for strong consistency
  - maximal security
  - simple to implement
  - failures are handled by the user
- Causal/PRAM consistency: distributed algorithms
  - predictable
  - not costly
  - no convergence
- Update consistency/strong eventual consistency: collaborative applications
  - close to self-stabilization
  - quite costly
  - inconsistencies visible to the user

Weak Consistency

Small experience with instant messaging:
Snapshat, Messenger, Whatsapp, Skype, Hangouts, etc.

- Hangouts: serializability
  - message sending can be aborted
- Whatsapp: PRAM consistency
  - local consistency (perhaps the least consistent instant messaging)
- Skype: strong eventual consistency
  - messages can be reordered afterwards (all users eventually see all messages in the same order)

Progress Conditions

- If one considers message-passing systems, when strong consistency is not possible, applications consider weak consistency as seen above.
  - Amazon's Dynamo highly available key-value store
- When necessary, whatever is the cost, strong consistency is provided
  - Apache's Zookeeper for maintaining configuration information
  - Google's Chubbby system
- In multithreaded computing, strong consistency is not sacrificed, but instead the progress condition is weakened: lock-free instead of wait-free

Progress Conditions

- The enqueue op. in Mickael & Scott's lock-free Queue (from D. Hendler)

```
public boolean enq(T value) {
  Node node=new Node(value);
  while (true) {
    Node last = tail.get();
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    if (last == tail.get()) {
       if (next == null) {
           if (last.next.compareAndSet(null,node) {
               tail.compareAndSet(last,node);
               return;
           }
        } else {
           tail.compareAndSet(last,next);
        }
      }
  }
}
```

Conclusion

- Lock-free implementation are less complex than wait-free ones but they offer weaker guarantees on progress
- In real settings, lock-free data structures statistically guarantee termination for all operations
- Mickael & Scott's lock-free linearizable queue is included in the Standard Java Concurrency Package
- There are many ongoing research to find the best special instructions and the most efficient distributed implementations of usual data structures