Another Look at the Implementation of Read/write Registers in Crash-prone Asynchronous Message-Passing Systems

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Table of contents

A glance at

Read/Write Registers

FUNDAMENTAL pbs of DC

- Communication
  - ⋆ Reliable broadcast
  - ⋆ Read/Write register
- Agreement

In the presence of adversaries
such as Asynchrony, failures, mobility, etc.

What is a register?

- Something that can be
  - ⋆ written (posted/marked) and
  - ⋆ read (understood)
- Historical perspective:
  - ⋆ One of the most ancient (3500 BC) ways to record history/information: Sumerian clay tablets
  - ⋆ More recently (1936): Turing machine tape: the fundamental object of computing

On the many faces of registers

- Capacity: binary, bounded, unbounded
- Access: SWSR, SWMR, MRMR
- Facing concurrency
  - ⋆ Safe register
  - ⋆ Regular register
  - ⋆ Atomic register
- From safe binary SWSR registers to atomic multivalued MWMR registers despite asynchrony and process crashes (Lamport 1986)
- In sequential computing:
  registers are universal objects (Turing, 1936)

Atomic read/write register

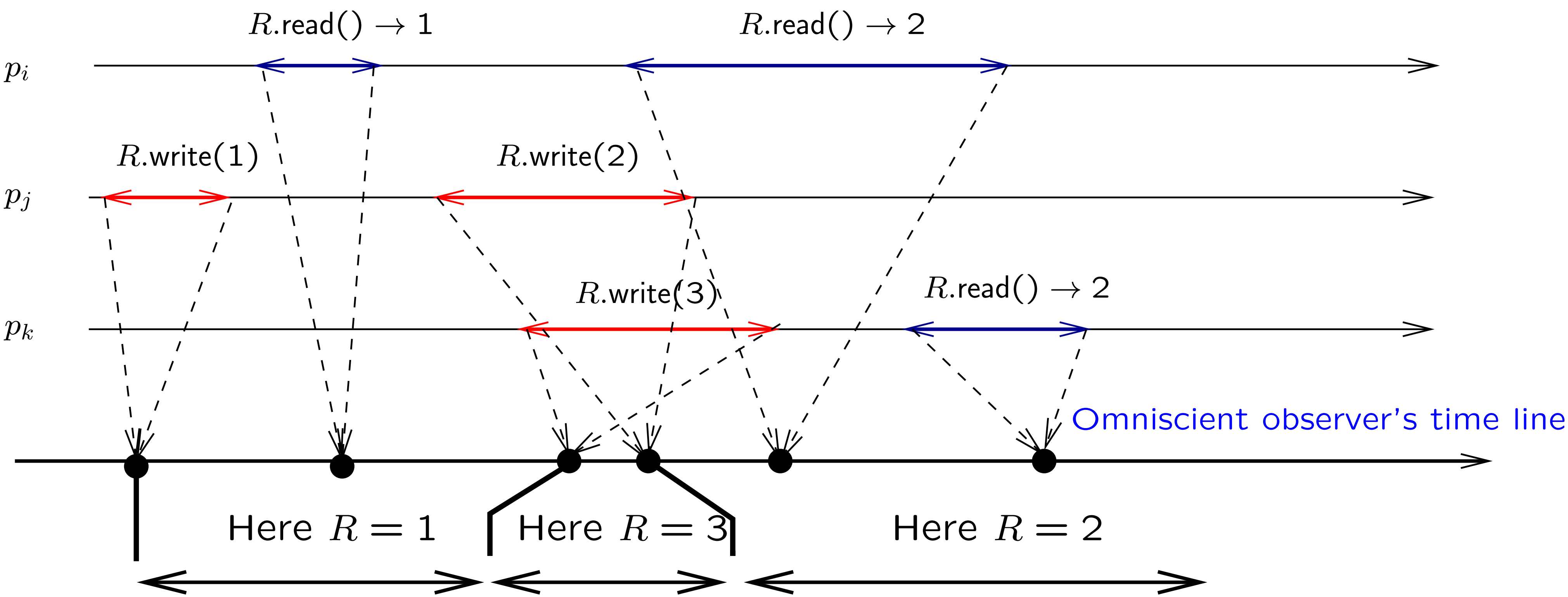
- Read and write operations appear as
  - ⋆ if they have been executed sequentially,
  - ⋆ and this sequence
    - ∗ complies with real-time order
      $\Rightarrow$ respects process order
    - ∗ satisfies the seq spec of a register
- Non-deterministic behavior when concurrency
- Why atomicity is fundamental:

Atomic objects compose for free!

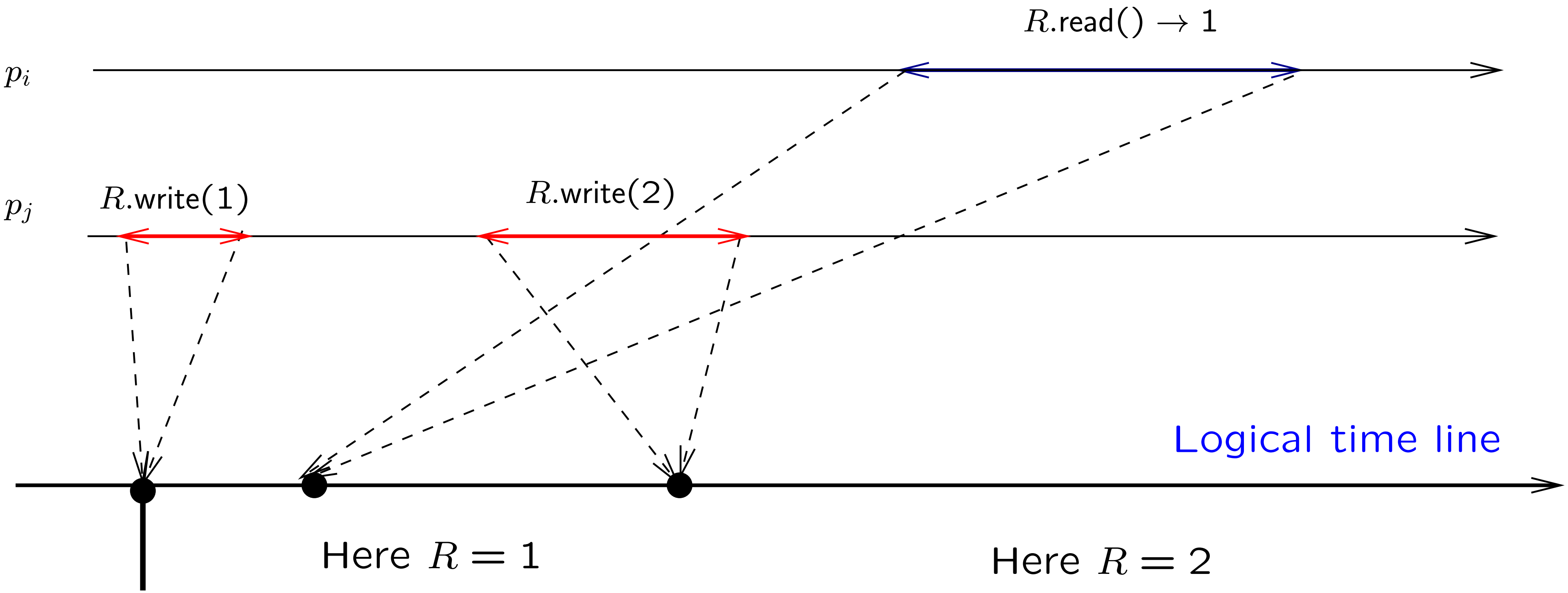
Sequentially consistent read/write register

- Read and write operations appear as
  - ⋆ if they have been executed sequentially,
  - ⋆ and this sequence
    - ∗ not required to comply with real-time order but respects process order
    - ∗ satisfies the seq spec of a register
- Non-deterministic behavior when concurrency
- Sequentially consistent objects do not compose for free!

Atomic read/write register: Example



Sequentially consistent read/write register: Example



Process and basic communication model

- Process model:
  - ⋆ n sequential processes p_1, ..., p_n
  - ⋆ asynchrony: unknown arbitrary speed
- Communication model:
  - ⋆ complete point-to-point network
  - ⋆ no bound on transfer delays (but finite)
  - ⋆ reliable (no loss, creation, duplication, alteration)
  - ⋆ point-to-point $\Rightarrow$ sender can be identified
  - ⋆ channels: not required to be FIFO

Communication operations

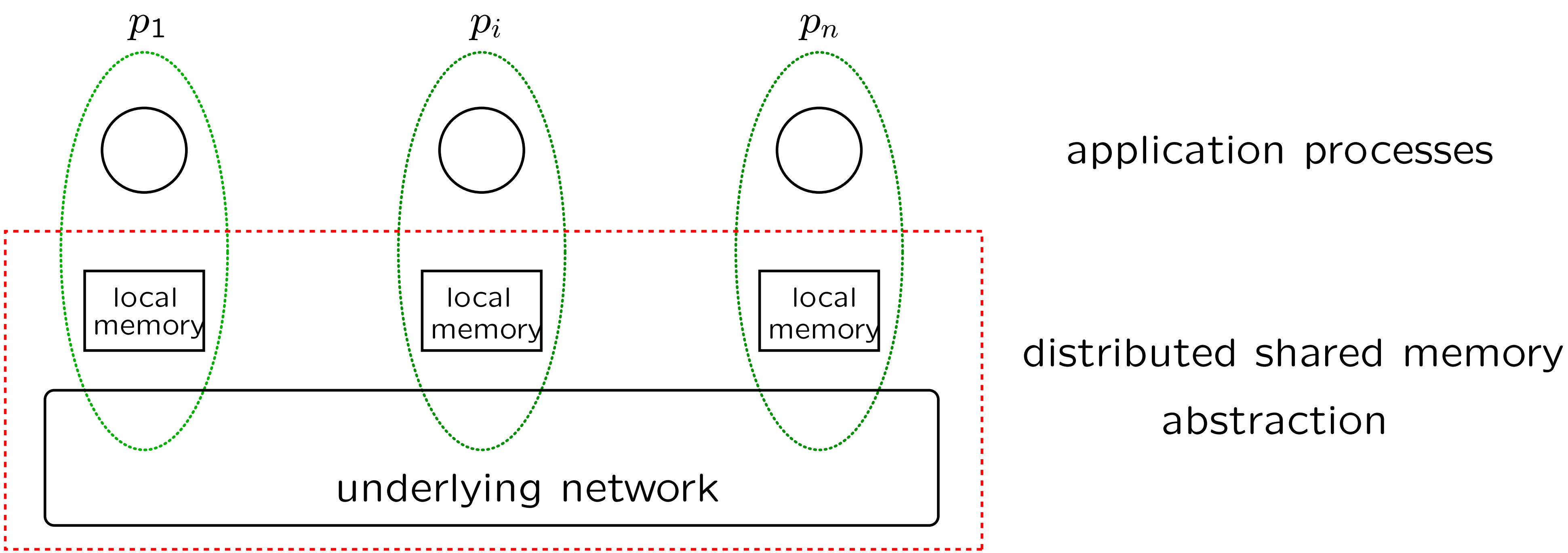
- operations "send tag (m) to p_j" and "receive ()"
- the macro-operation "broadcast tag (m)": shortcut for

for each $j \in \{1, \ldots, n\}$ send m to p_j **end for**

Process failure model

- Crash failure = unexpected halt
  - ⋆ A process executes correctly until it (possibly) crashes
  - ⋆ No recovery
- Model parameters n and t
  - ⋆ $\boxed{t}$ = upper bound on the nb of faulty processes
  - ⋆ Upper bound on t: $\boxed{t < n/2}$ (Attiya, Bar Noy, Dolev 1995)
  - ⋆ Notation: $\mathcal{CAMP}_{n,t}[\emptyset]$ and $\mathcal{CAMP}_{n,t}[t < n/2]$
- Broadcast is not reliable

Implementing a register REG in a MP system



Peer-to-peer system model

Each p_i is both a client and a server

Classical implementations of an atomic register

in crash-prone asynchronous message-passing systems

ABD95 algorithm: Dijkstra Prize 2011

- Attiya H., Bar-Noy A. and Dolev D., Sharing memory robustly in message passing systems. *Journal of the ACM*, 42(1):121-132 (1995)

- Impossibility to know if a process has crashed or is only very slow
- The problem can be solved iff $t < n/2$: proof based on indistinguishability argument
- Typical algorithm:
  - ⋆ Sequence numbers
  - ⋆ Notion of intersecting quorums
  - ⋆ Notion of requests and acknowledgments
    – Write copies of a majority of processes
    – Read copies from a majority of processes

A few other algorithms

- Attiya H., Efficient and robust sharing of memory in message-passing systems. *Journal of Algorithms*, 34:109-127 (2000)
- Delporte-Gallet C., Fauconnier H., Rajsbaum S., and Raynal M., Implementing snapshot objects on top of crash-prone asynchronous message-passing systems. *Proc. 16th Int'l Conference on Algorithms and Architectures for Parallel Processing (ICA3PP'16)*, Springer LNCS 10048, pp. 341–355 (2016)
- Hadjistasi Th., Nicolaou N., and Schwarzmann A.A., Oh-RAM! One and a half round read/write atomic memory. *Brief announcement. Proc. 35th ACM Symposium on Principles of Distributed Computing (PODC'16)*, ACM Press, pp. 353-355 (2016)
- Mostéfaoui A. and Raynal M., Two-bit messages are sufficient to implement atomic read/write registers in crash-prone systems. *Proc. 35th ACM Symposium on Principles of Distributed Computing (PODC'16)*, ACM Press, pp. 381-390 (2016)
- Raynal M., *Distributed algorithms for message-passing systems.* Springer, 510 pages, ISBN 978-3-642-38122-5 (2013)
- Ruppert E., Implementing shared registers in asynchronous message-passing systems. *Springer Encyclopedia of Algorithms*, pp. 400-403 (2008)

Aim of the paper

Objects to be built

- basic model $\mathcal{CARW}_{n,t}[\emptyset]$: Atomic read/write registers
- Snapshot objects (can be built in $\mathcal{CARW}_{n,t}[\emptyset]$)
  - ⋆ array $REG[1..m]$ of atomic read/write registers with two operations, write() and snapshot()
  - ⋆ MWMR snapshot
    - ∗ write(r, v) assigns v to $REG[r]$
    - ∗ snapshot() returns the value of the full array as if the operation had been executed instantaneously
  - ⋆ SWMR snapshot:
    - ∗ $m = n$ and
    - ∗ $r = i$ for write(r, v) by p_i

Which is

the communication abstraction

that matches

RW registers and snapshot objects?

and also help solve other problems...

More precisely

Concurrent object	Communication abstraction
Causal read/write registers	Causal msg delivery
Consensus	Total order broadcast
Snapshot object (R/W reg.)	SCD-broadcast

The SCD-Broadcast abstraction: definition (1)

SCD = Set-Constrained Delivery

- Two operations:
  - ⋆ scd_broadcast(m): broadcasts a message m
  - ⋆ scd_deliver(): returns a non-$\emptyset$ set of messages
- Five properties:
  - ⋆ Validity:
    If a process scd-delivers a set containing a message m, then m was scd-broadcast by some process
  - ⋆ Integrity:
    A msg is scd-delivered at most once by each process

The SCD-Broadcast abstraction: definition (2)

- MS-Ordering:
  A process p_i scd-delivers a message set ms_i containing a message m and later a message set ms'_i containing a message m'
  $\Rightarrow$
  no process scd-delivers first a message set ms'_j containing m' and later a message ms_j containing m

- Termination-1:
  If a non-faulty process scd-broadcasts a message m, it terminates its scd-broadcast invocation and scd-delivers a message set containing m

- Termination-2:
  If a process scd-delivers a message m, every non-faulty process scd-delivers a message set containing m

The SCD-Broadcast abstraction: PROPERTIES (1)

If each message set contains a single message

- Validity + Integrity + Termination-1 + Termination-2

= Uniform Reliable Broadcast

The SCD-Broadcast abstraction: PROPERTIES (2)

A containment property

- let ms_i^ℓ = ℓ-th message set scd-delivered by p_i
- at some time: p_i scd-delivered the sequence of message sets $ms_i^1, \cdots, ms_i^x$
- let $MS_i^x = ms_i^1 \cup \cdots \cup ms_i^x$
- let $MS_j^y = ms_i^1 \cup \cdots \cup ms_j^y$
- $\forall\ i, j, x, y$: $(MS_i^x \subseteq MS_j^y) \vee (MS_j^y \subseteq MS_i^x)$

The SCD-Broadcast abstraction: PROPERTIES (3)

Graph interpretation

- Local scd-delivery order: $m \mapsto_i m'$
  - $\star$ p_i scd-delivers a set containing m
  - $\star$ before a set containing m'
- Global scd-delivery order: $\mapsto \;=\; \cup_{1 \leq i \leq n} \mapsto_i$

$\mapsto$ is partial order (no cycle)
(useful to understand and proofs)

From SCD-Broadcast to MWMR Snapshot

Building a snapshot object in $\mathcal{CAMP}_{n,t}$[SCD-broadcast]

Local representation of the snapshot object REG

- $reg_i[1..m]$: current value of $REG[1..m]$, as known by p_i
- $done_i$: Boolean variable
- $tsa_i[1..m]$: array of timestamps associated with the values stored in $reg_i[1..m]$
  - ⋆ $tsa_i[j].date$ and $tsa_i[j].proc$ (timestamp of $reg_i[j]$)
- Lexicographical total order $<_{ts}$:
  - ⋆ $ts1 = \langle h1, i1 \rangle$ and $ts2 = \langle h2, i2 \rangle$
  - ⋆ $ts1 \;<_{ts}\; ts2 \overset{def}{=} (h1 < h2) \vee ((h1 = h2) \wedge (i1 < i2))$

Algorithm: snapshot operation

operation snapshot() **by** p_i **is**

$done_i \leftarrow$ `false`;

scd_broadcast SYNC (i);

wait($done_i$); % end of synchronization

return($reg_i[1..m]$).

- SYNC (i) synchronization message
- allows p_i to obtain an atomic value of $REG[1..m]$

Algorithm: write operation

operation write(r, v) **by** p_i **is**

$done_i \leftarrow$ `false`;
scd_broadcast SYNC (i);
wait$(done_i)$; % end of synchronization 1
$done_i \leftarrow$ `false`;
scd_broadcast WRITE $(r, v, \langle tsa_i[r].date + 1, i \rangle)$;
wait$(done_i)$. % end of synchronization 2

Algorithm: snapshot operation

when the message set
$\{$WRITE$(r_{j_1}, v_{j_1}, \langle date_{j_1}, j_1\rangle)$, $\cdots$, WRITE$(r_{j_x}, v_{j_x}, \langle date_{j_x}, j_x\rangle)$,
SYNC(j_{x+1}), $\cdots$, SYNC(j_y) $\}$ **is scd-delivered do**

for each r such that WRITE$(r, -, -) \in$ the message set **do**
  let $\langle date, writer\rangle$ = greatest timestamp in WRITE$(r, -, -)$;
  if $(tsa_i[r] \;<_{ts}\; \langle date, writer\rangle)$
    then let v the value in WRITE$(r, -, \langle date, writer\rangle)$;
      $reg_i[r] \leftarrow v$; $tsa_i[r] \leftarrow \langle date, writer\rangle$
  end if
end for;
if $\exists\, \ell : j_\ell = i$ **then** $done_i \leftarrow \texttt{true}$ **end if**.

Observation: no quorum at this abstraction level!

The case of a sequentially consistent snapshot object

Suppress the messages SYNC!

These messages ensure compliance wrt real-time

operation snapshot() **by** p_i **is**
return($reg_i[1..m]$).

operation write(r, v) **by** p_i **is**
$done_i \leftarrow$ `false`;
scd_broadcast WRITE $(r, v, \langle tsa_i[r].date + 1, i\rangle)$;
wait($done_i$).

when the message set
$\{$WRITE$(r_{j1}, v_{j1}, \langle date_{j1}, j1\rangle), \cdots,$ WRITE$(r_{jx}, v_{jx}, \langle date_{jx}, jx\rangle)\}$
is scd-delivered do ....

From MWMR Snapshot to SCD-Broadcast

Building SCD-Broadcast in $\mathcal{CARW}_{n,t}$[Snapshot] ($\mathcal{CARW}_{n,t}[\emptyset]$)

Shared objects

ϵ: empty sequence
$\oplus$: concatenation

- $SENT[1..n]$: snapshot object, initialized to $[\emptyset, \cdots, \emptyset]$
  $SENT[i]$ = messages scd-broadcast by p_i
- $SETS\_SEQ[1..n]$: snapshot object, initialized to $[\epsilon, \cdots, \epsilon]$
  $SETS\_SEQ[i]$ = seq. of msg sets scd-delivered by p_i

Local objects

- $sent_i$: local copy of the snapshot object $SENT$
- $sets\_seq_i$: local copy of the snapshot object $SETS\_SEQ$.
- $to\_deliver_i$: set whose aim is to contain the next message set that p_i has to scd-deliver
- members(set_seq) returns the set of messages in set_seq

Algorithm (1)

operation scd_broadcast(m) **by** p_i **is**

$sent_i[i] \leftarrow sent_i[i] \cup \{m\}$; $SENT$.write($sent_i[i]$); progress().

background task T **is**

repeat forever progress() **end repeat**.

Algorithm (2)

```
procedure progress() by p_i is
    enter_mutex();
    catch_up();
    sent_i ← SENT.snapshot();
    to_deliver_i ← (∪_{1≤j≤n} sent_i[j]) \ members(sets_seq_i[i]);
    if (to_deliver_i ≠ ∅)
       then sets_seq_i[i] ← sets_seq_i[i] ⊕ to_deliver_i;
            SETS_SEQ.write(i, sets_seq_i[i]);
            scd_deliver(to_deliver_i)
    end if;
    exit_mutex().
```

Algorithm (3)

procedure catch_up() **by** p_i **is**
  $sets\_seq_i \leftarrow SETS\_SEQ$.snapshot();
  while
    $(\exists j, set :$ set first set in $sets\_seq_i[j] \wedge set \not\subseteq$ members$(sets_seq_i[i])$
    do $to\_deliver_i \leftarrow set \setminus$ members$(sets_seq_i[i])$;
      $sets\_seq_i[i] \leftarrow sets\_seq_i[i] \oplus to\_deliver_i$;
      $SETS\_SEQ$.write$(i, sets_seq_i[i])$;
      scd_deliver$(to_deliver_i)$
  end while.

From sequentially consistency to atomicity

From non-composable to composable snapshot objects

The power of the messages SYNC() (real-time compliance)

- Start from a sequentially consistent snapshot object ($\mathcal{CARW}_{n,t}$[Snapshot])
- Build SCD-Broadcast on top of it

  we obtain $\mathcal{CAMP}_{n,t}$[SCD-broadcast]
- Build atomic snapshot on top of $\mathcal{CAMP}_{n,t}$[SCD-broadcast]

First (?) systematic construction from SC to Atomicity

On the implementation of SCD-Broadcast

Implementing SCD in $\mathcal{CAMP}\{t < n/2\}$

operation scd_broadcast(m) **is**
  forward(m, i, sn_i, i, sn_i);
  wait($\nexists\ msg \in buffer_i : msg.sd = i$).

when the message forward(m, sd, sn_{sd}, f, sn_f) **is fifo-delivered do** % from p_f
  forward(m, sd, sn_{sd}, f, sn_f);
  try_deliver().

procedure forward(m, sd, sn_{sd}, f, sn_f) **is**
  if ($sn_{sd} > clock_i[sd]$)
   then if ($\exists\ msg \in buffer_i : msg.sd = sd \wedge msg.sn = sn_{sd}$)
      then $msg.cl[f] \leftarrow sn_f$
      else $threshold[1..n] \leftarrow [\infty, \ldots, \infty]$; $threshold[f] \leftarrow sn_f$;
        let $msg \leftarrow \langle m, sd, sn_{sd}, threshold[1..n] \rangle$;
        $buffer_i \leftarrow buffer_i \cup \{msg\}$;
        fifo_broadcast forward(m, sd, sn_{sd}, i, sn_i);
        $sn_i \leftarrow sn_i + 1$
     end if
  end if.

Implementing SCD in $\mathcal{CAMP}\{t < n/2\}$ (Cont'd)

procedure try_deliver() **is**
  let $to\_deliver_i \leftarrow \{msg \in buffer_i : |\{f : msg.cl[f] < \infty\}| > \frac{n}{2}\}$;
while $(\exists msg \in to\_deliver_i, msg' \in buffer_i \setminus to\_deliver_i : |\{f : msg.cl[f] < msg'.cl[f]\}| \leq \frac{n}{2})$ **do**
    $to\_deliver_i \leftarrow to\_deliver_i \setminus \{msg\}$
  end while;
  if $(to\_deliver_i \neq \emptyset)$
   then for each ($msg \in to\_deliver_i$ such that $clock_i[msg.sd] < msg.sn$)
        do $clock_i[msg.sd] \leftarrow msg.sn$ **end for**;
      $buffer_i \leftarrow buffer_i \setminus to\_deliver_i$;
      $ms \leftarrow \{m : \exists\ msg \in to\_deliver_i : msg.m = m\}$; scd_deliver($ms$)
  end if.

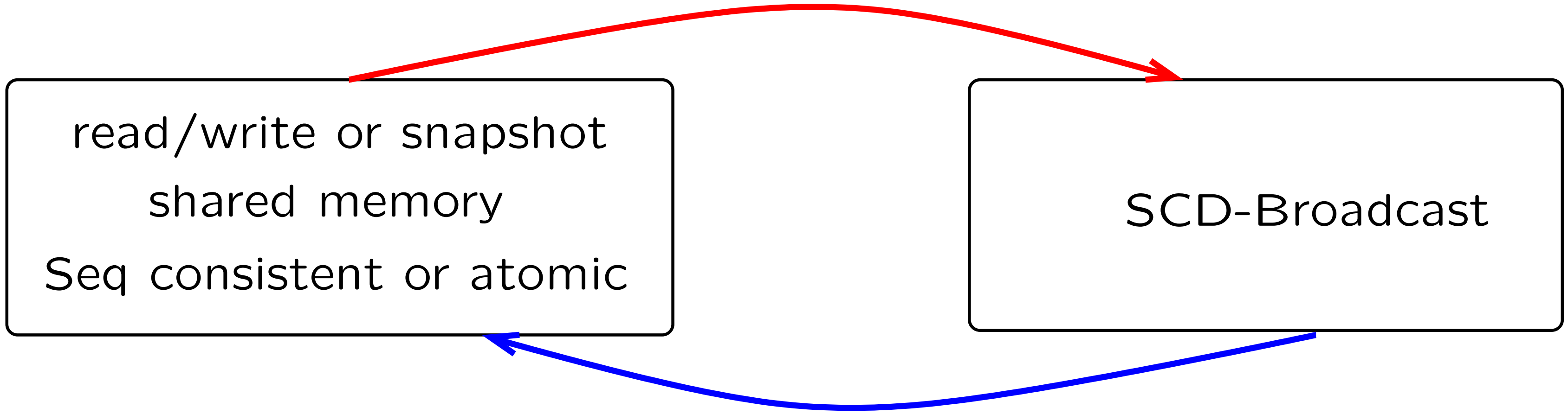
- As $t < n/2$ is necessary and sufficient to build read/write registers in $\mathcal{CAMP}_{n,t}[\emptyset]$, it is also necessary ans sufficient to build SCD-broadcast in $\mathcal{CAMP}_{n,t}[\emptyset]$
- All the "technical details" are hidden in this algorithm which is designed and proved once for all!

Cost of SCD-broadcast implementation

- Assumption:
  - $\star$ Let Δ = message delay
  - $\star$ Local computation: zero cost
- Cost:
  - $\star$ Time: 2Δ
  - $\star$ Messages: n^2

Conclusion

To summarize



Other applications:
lattice agreement, commutative operations, ...

Conceptual issues

- Better understanding of basic mechanisms needed to implement a read/write shared memory
- SCD-broadcast captures the "right" abstraction level
- Simplicity of the proposed (register/snapshot) algo.
- Genericity of the proposed algorithms wrt
  - ⋆ read/write vs snapshot objects (same algorithms)
  - ⋆ atomicity vs sequential consistency (SYNC msgs)

More important: He Told me

"Algorithms are at the core of Informatics"