On Verifying Causal Consistency

Ahmed Bouajjani, Constantin Enea, Rachid Guerraoui, Jad Hamza

IRIF, Université Paris Diderot

May 2017

European Research Council
Established by the European Commission

Geo-Replicated Data Structures

- Strong (sequential) consistency

[1] S. Gilbert and N. A. Lynch. Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services.

Geo-Replicated Data Structures

- Strong (sequential) consistency

[1]S. Gilbert and N. A. Lynch. Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services.

Geo-Replicated Data Structures

- Strong (sequential) consistency

[1] S. Gilbert and N. A. Lynch. Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services.

Geo-Replicated Data Structures

- Strong (sequential) consistency is impossible while being **available** and tolerating **network partitions**: the CAP theorem [1]

[1] S. Gilbert and N. A. Lynch. Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services.

Geo-Replicated Data Structures

- Tolerating **faults** while preserving **availability** leads to anomalies w.r.t. strong (sequential) consistency

Geo-Replicated Data Structures

- Tolerating **faults** while preserving **availability** leads to anomalies w.r.t. strong (sequential) consistency

`write`$(x, 2)$ `write`$(x, 1)$

Geo-Replicated Data Structures

- Tolerating **faults** while preserving **availability** leads to anomalies w.r.t. strong (sequential) consistency

Updates are seen in different orders

Goal: Verifying Causal Consistency

The set of allowed anomalies are defined by **weak consistency** criteria, e.g., eventual consistency, causal consistency.

Algorithmic methods for checking **causal consistency**.

Single-Trace Verification: Check if one trace is causally consistent

- Application to testing, monitoring (by enumerating traces)

All-Traces Verification: Check if all traces are causally consistent

- Static verification

Comparison with other Consistency Criteria

Single-Trace Verification:

- NP-**complete** for most consistency criteria[2]

[3] Memory Model-aware Testing. Furbach et al. 2014.
[4] Model-Checking of Correctness Conditions. Alur et al. 1996.
[5] On the complexity of linearizability. H. 2015.
[6] Verifying Eventual Consistency of ORS. Bouajjani et al. 2014.

Comparison with other Consistency Criteria

Single-Trace Verification:

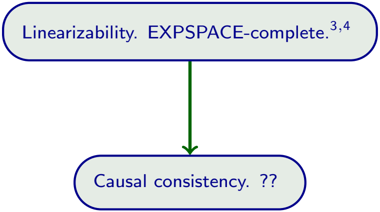
- NP-**complete** for most consistency criteria[2]
- NP-**complete** for causal consistency as well

[3] Memory Model-aware Testing. Furbach et al. 2014.
[4] Model-Checking of Correctness Conditions. Alur et al. 1996.
[5] On the complexity of linearizability. H. 2015.
[6] Verifying Eventual Consistency of ORS. Bouajjani et al. 2014.

Comparison with other Consistency Criteria

Single-Trace Verification:

- NP-**complete** for most consistency criteria[2]
- NP-**complete** for causal consistency as well



All-Traces Verification:

- EXPSPACE-**complete** for **linearizability**[3,4]

---

[3] Memory Model-aware Testing. Furbach et al. 2014.
[4] Model-Checking of Correctness Conditions. Alur et al. 1996.
[5] On the complexity of linearizability. H. 2015.
[6] Verifying Eventual Consistency of ORS. Bouajjani et al. 2014.

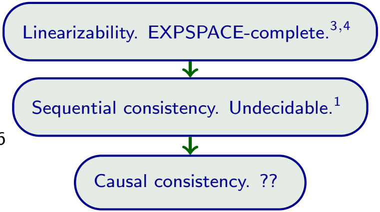
Comparison with other Consistency Criteria

Single-Trace Verification:

- NP-**complete** for most consistency criteria[2]
- NP-**complete** for causal consistency as well

All-Traces Verification:

- EXPSPACE-**complete** for **linearizability**[3,4]
- **Undecidable** for **sequential consistency**[5,6]



[3] Memory Model-aware Testing. Furbach et al. 2014.
[4] Model-Checking of Correctness Conditions. Alur et al. 1996.
[5] On the complexity of linearizability. H. 2015.
[6] Verifying Eventual Consistency of ORS. Bouajjani et al. 2014.

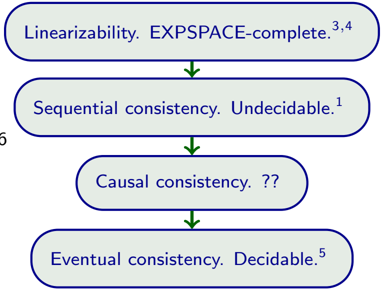
Comparison with other Consistency Criteria

Single-Trace Verification:

- NP-**complete** for most consistency criteria[2]
- NP-**complete** for causal consistency as well

All-Traces Verification:

- EXPSPACE-**complete** for **linearizability**[3,4]
- **Undecidable** for **sequential consistency**[5,6]
- **Decidable** for eventual consistency[7]



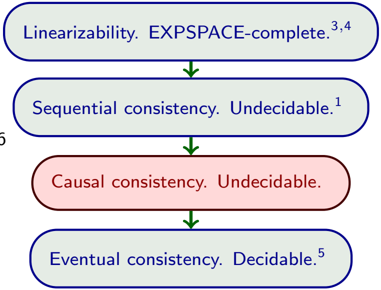
---

[3] Memory Model-aware Testing. Furbach et al. 2014.
[4] Model-Checking of Correctness Conditions. Alur et al. 1996.
[5] On the complexity of linearizability. H. 2015.
[6] Verifying Eventual Consistency of ORS. Bouajjani et al. 2014.

Comparison with other Consistency Criteria

Single-Trace Verification:

- **NP-complete** for most consistency criteria[2]
- **NP-complete** for causal consistency as well



All-Traces Verification:

- **EXPSPACE-complete** for **linearizability**[3,4]
- **Undecidable** for **sequential consistency**[5,6]
- **Decidable** for eventual consistency[7]
- **Undecidable** for causal consistency

[3] Memory Model-aware Testing. Furbach et al. 2014.
[4] Model-Checking of Correctness Conditions. Alur et al. 1996.
[5] On the complexity of linearizability. H. 2015.
[6] Verifying Eventual Consistency of ORS. Bouajjani et al. 2014.

What About Usual Data Structures?

Key-value store (read/write operations):
one of the **simplest** and most **widely used** data structures.

What About Usual Data Structures?

Key-value store (read/write operations):
one of the **simplest** and most **widely used** data structures.

Theorem (All-Traces Verification)

Checking if **all traces** *of an implementation are causally consistent is* **undecidable**.

What About Usual Data Structures?

Key-value store (read/write operations):
one of the **simplest** and most **widely used** data structures.

Theorem (All-Traces Verification)

*Checking if **all traces** of an implementation are causally consistent is **undecidable**.*

Even with the following restrictions:

- For **key-value stores**
- For a bounded number of **sites**
- For **finite-state** implementations
- For a bounded number of **variables**
- For a bounded variables' **domain**

What About Usual Data Structures?

Key-value store (read/write operations):
one of the **simplest** and most **widely used** data structures.

Theorem (All-Traces Verification)

Checking if **all traces** *of an implementation are causally consistent is* **undecidable**.

Even with the following restrictions:

- For **key-value stores**
- For a bounded number of **sites**
- For **finite-state** implementations
- For a bounded number of **variables**
- For a bounded variables' **domain**

(Input: **finite-state automaton** representing all traces)

Key Observation: Implementations Are Data Independent

Key-value store implementations are **data independent**

The **behaviors** do not depend on the particular values stored in the KVS.

Key Observation: Implementations Are Data Independent

Key-value store implementations are **data independent**

The **behaviors** do not depend on the particular values stored in the KVS.

⇒ **Writes can be assumed to be unique**

Results: Causal Consistency Violations Using Bad Patterns

Bad Pattern: A set of operations **related** in a particular way

Results: Causal Consistency Violations Using Bad Patterns

Bad Pattern: A set of operations **related** in a particular way

Identify **a set of bad patterns** X such that:

Theorem (Bad Patterns)

A trace is **not causally consistent** *iff it contains some* **bad pattern** *from* X

Results: Causal Consistency Violations Using Bad Patterns

Bad Pattern: A set of operations **related** in a particular way

Identify **a set of bad patterns** X such that:

Theorem (Bad Patterns)

A trace is **not causally consistent** *iff it contains some* **bad pattern** *from* X

X contains **4-6** bad patterns

Results: Complexity/Decidability and Reduction to Reachability

Bad patterns implications for **data-independent** implementations:

Theorem (Single-Trace Verification)

Singe-Trace Verification of causal consistency is **polynomial** *when* **writes are unique***.*

Results: Complexity/Decidability and Reduction to Reachability

Bad patterns implications for **data-independent** implementations:

Theorem (Single-Trace Verification)

Singe-Trace Verification of causal consistency is **polynomial** *when* **writes are unique**.

Theorem (Reduction to Reachability)

All-Traces Verification can be reduced to **reachability** *or* **invariant checking**.
(by building a monitor (state machine) M that tracks bad patterns)

Results: Complexity/Decidability and Reduction to Reachability

Bad patterns implications for **data-independent** implementations:

Theorem (Single-Trace Verification)

Singe-Trace Verification of causal consistency is **polynomial** *when* **writes are unique**.

Theorem (Reduction to Reachability)

All-Traces Verification can be reduced to **reachability** *or* **invariant checking**. *(by building a monitor (state machine) M that tracks bad patterns)*

Theorem (All-Traces Verification)

Checking whether **all traces** *of a* **data-independent** *finite-state implementation are causally consistent is* **decidable**.

Outline

- Definition(s) of **causal consistency**

Outline

- Definition(s) of **causal consistency**
- Characterize **all causal consistency violations** using bad patterns

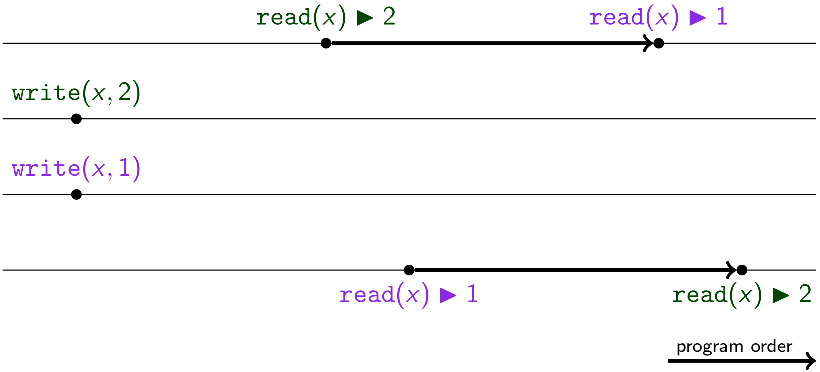
Outline

- Definition(s) of **causal consistency**
- Characterize **all causal consistency violations** using bad patterns
- Using bad patterns for verifying data-independent implementations
  - Single-Trace Verification: **polynomial time**
  - **Bad patterns** can be recognized with **state machines**
  - **Generic reduction** from causal consistency to **reachability**
  - All-Traces Verification: **decidable**

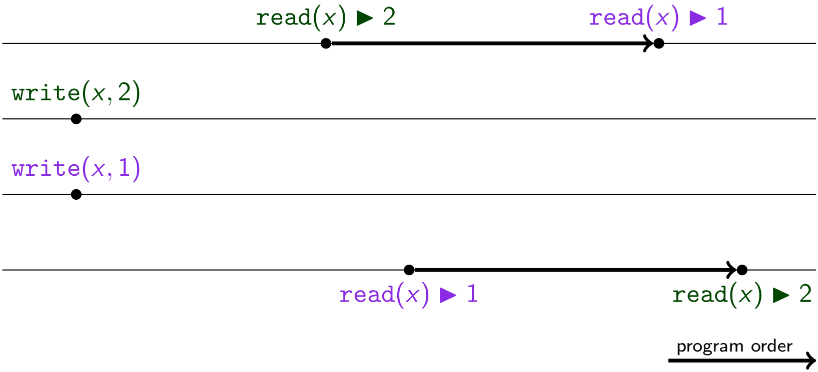
Outline

- Definition(s) of **causal consistency**
- Characterize **all causal consistency violations** using bad patterns
- Using bad patterns for verifying data-independent implementations
  - Single-Trace Verification: **polynomial time**
  - **Bad patterns** can be recognized with **state machines**
  - **Generic reduction** from causal consistency to **reachability**
  - All-Traces Verification: **decidable**

Definition of Causal Consistency



Definition of Causal Consistency

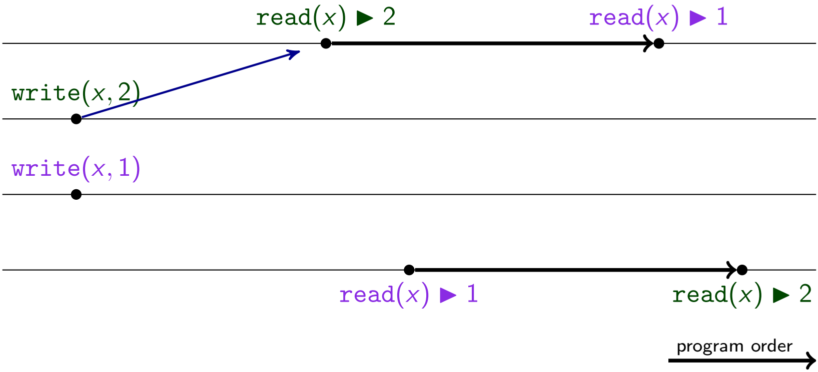


There exists a **causality order** *CO* such that

the causal past of every read can explain its value

CO includes the program (site) order

Definition of Causal Consistency

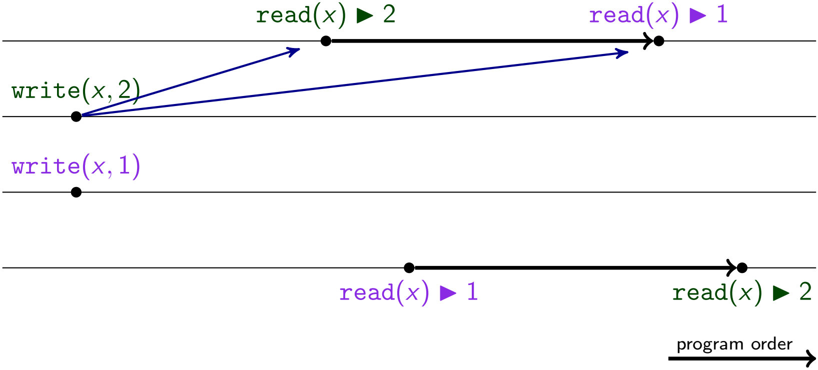


There exists a **causality order** *CO* such that

the causal past of every read can explain its value

CO includes the program (site) order

Definition of Causal Consistency

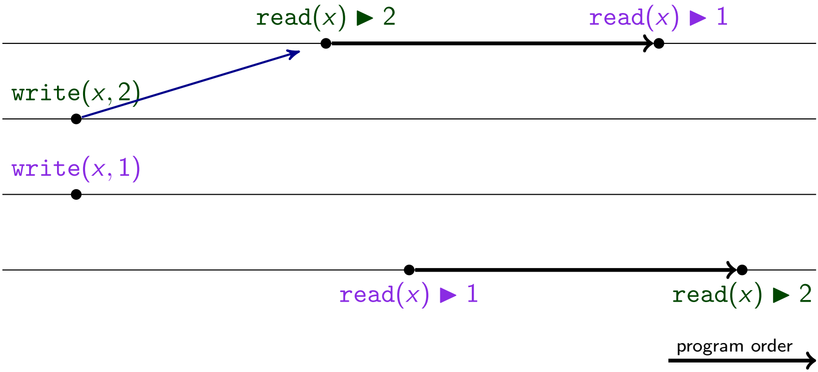


There exists a **causality order** *CO* such that

the causal past of every read can explain its value

CO includes the program (site) order

Definition of Causal Consistency

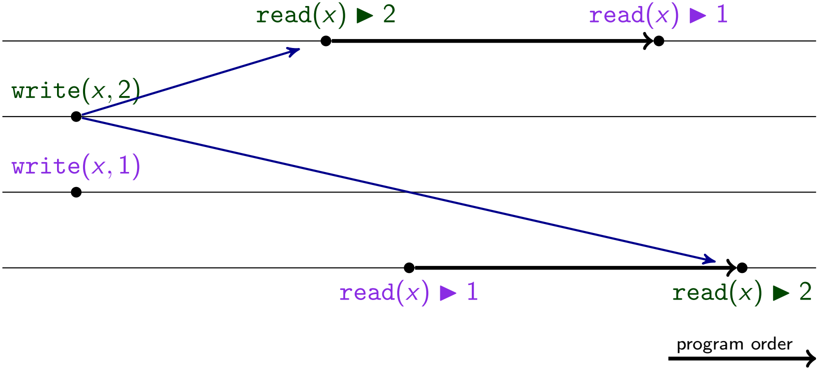


There exists a **causality order** *CO* such that

the causal past of every read can explain its value

CO includes the program (site) order

Definition of Causal Consistency

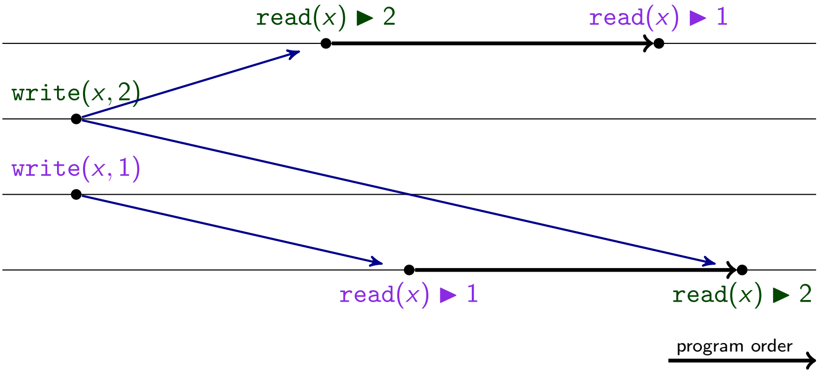


There exists a **causality order** *CO* such that

the causal past of every read can explain its value

CO includes the program (site) order

Definition of Causal Consistency

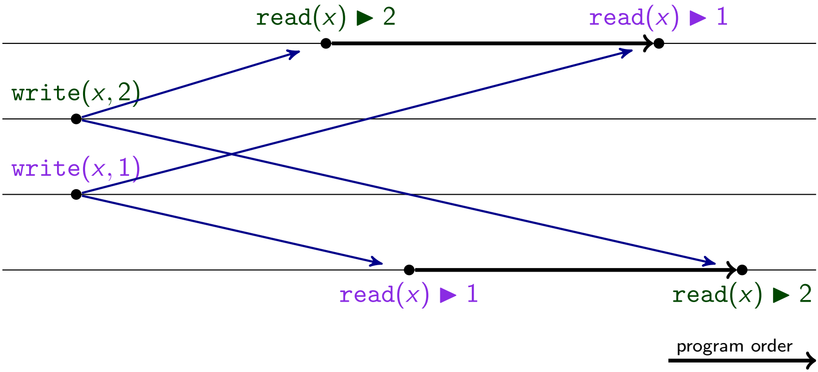


There exists a **causality order** *CO* such that

the causal past of every read can explain its value

CO includes the program (site) order

Definition of Causal Consistency

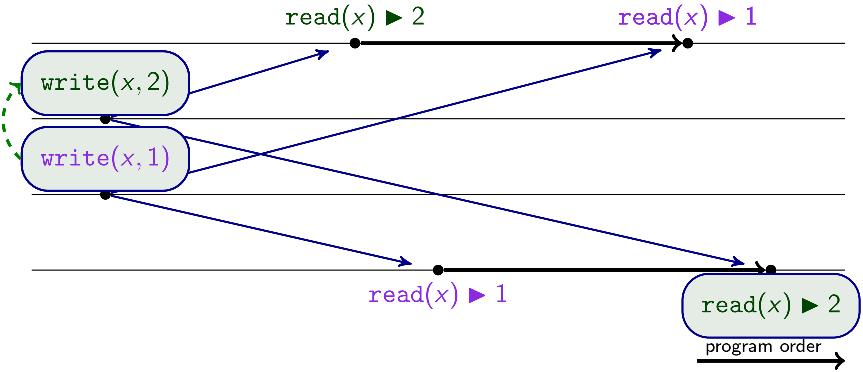


There exists a **causality order** *CO* such that

the causal past of every read can explain its value

CO includes the program (site) order

Definition of Causal Consistency

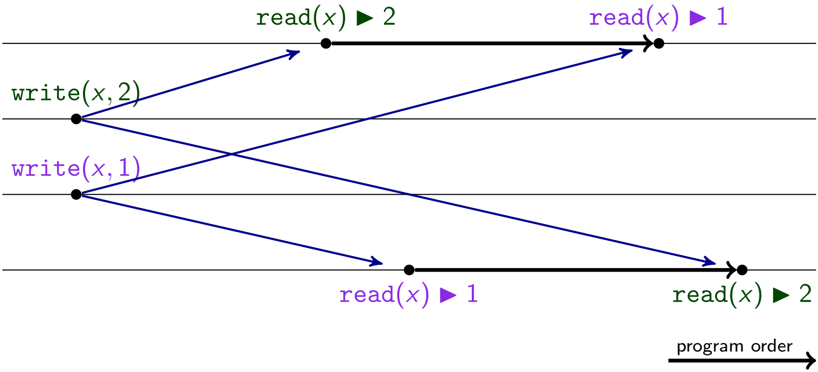


There exists a **causality order** *CO* such that

the causal past of every read can explain its value

CO includes the program (site) order

Definition of Causal Consistency

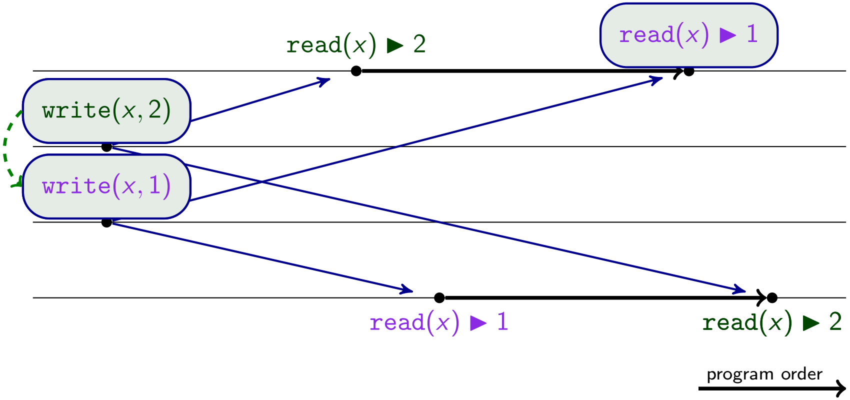


There exists a **causality order** *CO* such that

the causal past of every read can explain its value

CO includes the program (site) order

Definition of Causal Consistency



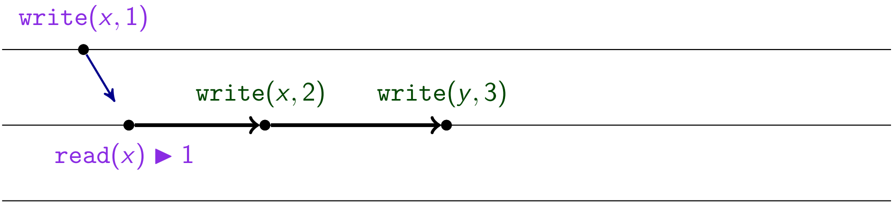
There exists a **causality order** *CO* such that

the causal past of every read can explain its value

CO includes the program (site) order

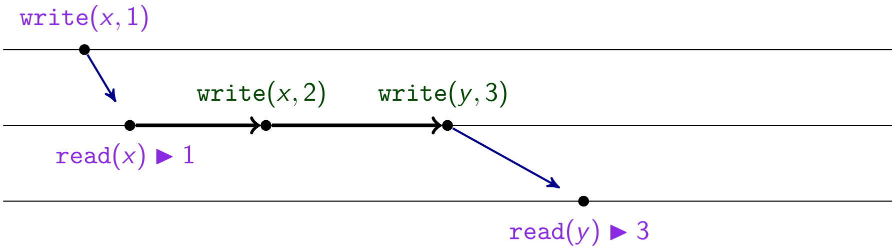
Causal Consistency Violations

Causally related *writes must be seen by all sites in the same order.*



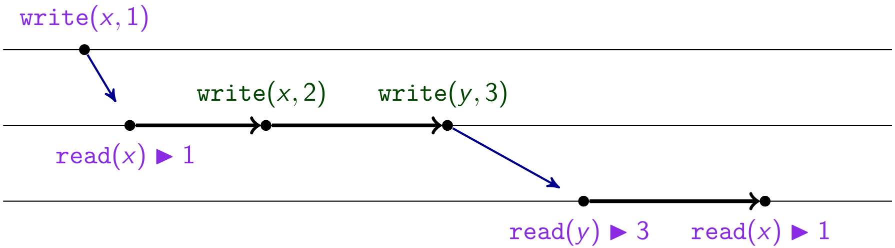
Causal Consistency Violations

Causally related *writes must be seen by all sites in the same order.*



Causal Consistency Violations

Causally related *writes must be seen by all sites in the same order.*



Formalizing Causal Consistency

Specification = a set of sequences of operations

- $\mathtt{write}(x, 1) \cdot \mathtt{write}(y, 2) \cdot \mathtt{read}(x) \blacktriangleright 1 \cdot \mathtt{read}(y) \blacktriangleright 2$

Formalizing Causal Consistency

Specification = a set of sequences of operations

- $\texttt{write}(x, 1) \cdot \texttt{write}(y, 2) \cdot \texttt{read}(x) \blacktriangleright 1 \cdot \texttt{read}(y) \blacktriangleright 2$

A history $h = (O, PO)$ is **causally consistent** w.r.t. a specification S iff there exists a strict partial order CO s.t.

Formalizing Causal Consistency

Specification = a set of sequences of operations

- $\texttt{write}(x, 1) \cdot \texttt{write}(y, 2) \cdot \texttt{read}(x) \blacktriangleright 1 \cdot \texttt{read}(y) \blacktriangleright 2$

A history $h = (O, PO)$ is **causally consistent** w.r.t. a specification S iff there exists a strict partial order CO s.t.

$$\textsc{AxCausal}: \; PO \subseteq CO$$

Formalizing Causal Consistency

Specification = a set of sequences of operations

- $\texttt{write}(x, 1) \cdot \texttt{write}(y, 2) \cdot \texttt{read}(x) \blacktriangleright 1 \cdot \texttt{read}(y) \blacktriangleright 2$

A history $h = (O, PO)$ is **causally consistent** w.r.t. a specification S iff there exists a strict partial order CO s.t.

$$\textsc{AxCausal}: \quad PO \subseteq CO$$

$$\textsc{AxCausalValue}: \quad \forall o \in O.\ \mathsf{CausalPast}(CO, o) \sqsubseteq S$$

Formalizing Causal Consistency

Specification = a set of sequences of operations

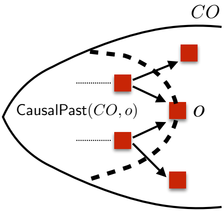
- $\mathtt{write}(x,1) \cdot \mathtt{write}(y,2) \cdot \mathtt{read}(x) \blacktriangleright 1 \cdot \mathtt{read}(y) \blacktriangleright 2$

A history $h = (O, PO)$ is **causally consistent** w.r.t. a specification S iff there exists a strict partial order CO s.t.

$$\textsc{AxCausal}: \quad PO \subseteq CO$$

$$\textsc{AxCausalValue}: \quad \forall o \in O.\ \mathsf{CausalPast}(CO, o) \sqsubseteq S$$

$$(\mathsf{CausalPast}(CO, o) = \text{the restriction of } CO \text{ to } CO^{-1}(o) \cup \{o\}$$



Formalizing Causal Consistency

Specification = a set of sequences of operations

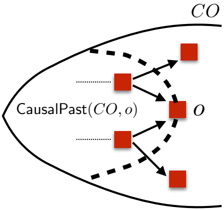
- $\mathtt{write}(x, 1) \cdot \mathtt{write}(y, 2) \cdot \mathtt{read}(x) \blacktriangleright 1 \cdot \mathtt{read}(y) \blacktriangleright 2$

A history $h = (O, PO)$ is **causally consistent** w.r.t. a specification S iff there exists a strict partial order CO s.t.

$$\textsc{AxCausal}: \quad PO \subseteq CO$$

$$\textsc{AxCausalValue}: \quad \forall o \in O.\ \mathsf{CausalPast}(CO, o) \sqsubseteq S$$

($\mathsf{CausalPast}(CO, o)$ = the restriction of CO to $CO^{-1}(o) \cup \{o\}$



$\sqsubseteq$ means "can be linearized to")

Causal Convergence[8]

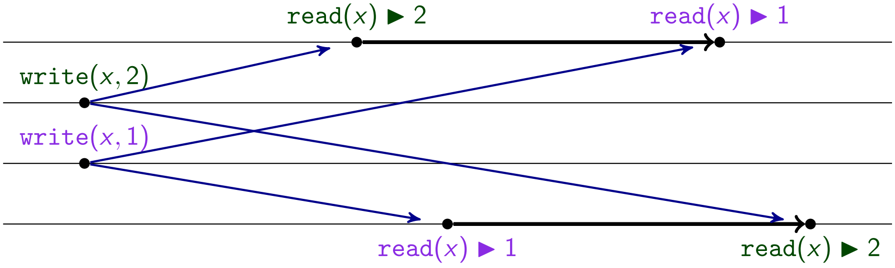
- Conflicts are resolved using a global **arbitration order**
- **Strong eventual consistency**:
  If two sites see the same writes, they are in the same state[7]

[7] A comprehensive study of CRDTs. 2011. Shapiro et al.
[8] Understanding Eventual Consistency. Burckhardt et al. 2013.

Causal Convergence[8]

- Conflicts are resolved using a global **arbitration order**
- **Strong eventual consistency**:
  If two sites see the same writes, they are in the same state[7]

Not allowed by causal convergence:



[7] A comprehensive study of CRDTs. 2011. Shapiro et al.
[8] Understanding Eventual Consistency. Burckhardt et al. 2013.

Causal Convergence

A history $h = (O, PO)$ is **causally convergent** w.r.t. a specification S iff there exists a strict partial order CO and a strict total order ARB (**arbitration**) s.t.

Causal Convergence

A history $h = (O, PO)$ is **causally convergent** w.r.t. a specification S iff there exists a strict partial order CO and a strict total order ARB (**arbitration**) s.t.

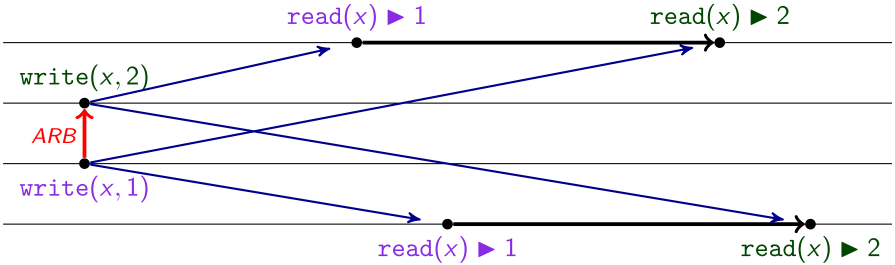
$$\textsc{AxCausal}: \; PO \subseteq CO$$

$$\textsc{AxArb}: \; CO \subseteq ARB$$

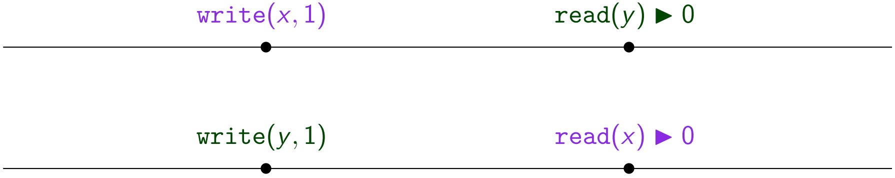
$$\textsc{AxCausalArb}: \; \forall o \in O.\ \mathsf{CausalPast}(CO, o) \oplus ARB \in S$$

($\mathsf{CausalPast}(CO, o) =$ the restriction of CO to $CO^{-1}(o) \cup \{o\}$
"$\oplus\ ARB$" means adding the constraints in ARB)

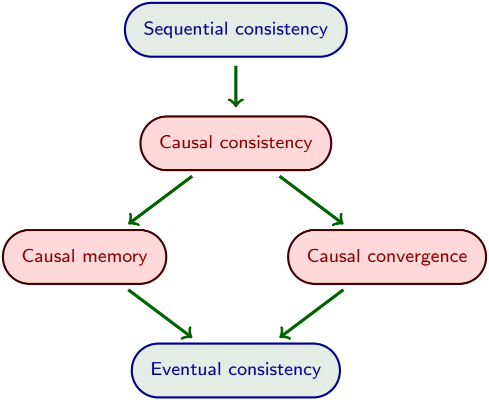
Satisfying Causal Convergence



Satisfying Causal Convergence but not Sequential Consistency



Different Notions of Causal Consistency



Causal memory = Causal consistency + local arbitration

Outline

- Definition(s) of **causal consistency**
- Characterize **all causal consistency violations** using bad patterns
- Using bad patterns for verifying data-independent implementations
  - Single-Trace Verification: **polynomial time**
  - **Bad patterns** can be recognized with **state machines**
  - **Generic reduction** from causal consistency to **reachability**
  - All-Traces Verification: **decidable**

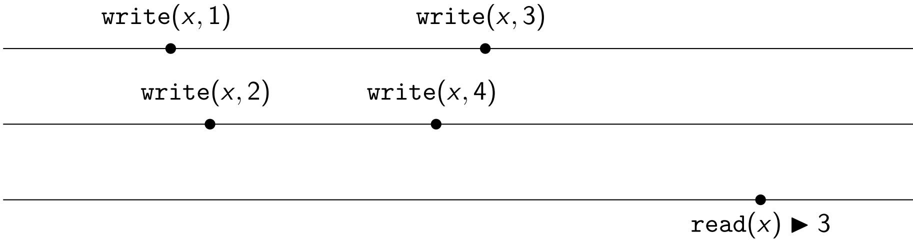
Data Independent Implementations

Observation: Written values do not influence behaviors.

$\Rightarrow$ We can assume written values are unique.

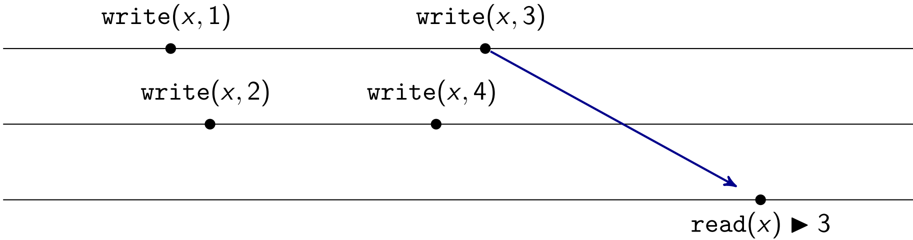
Data Independent Implementations

Observation: Written values do not influence behaviors.
⇒ We can assume written values are unique.



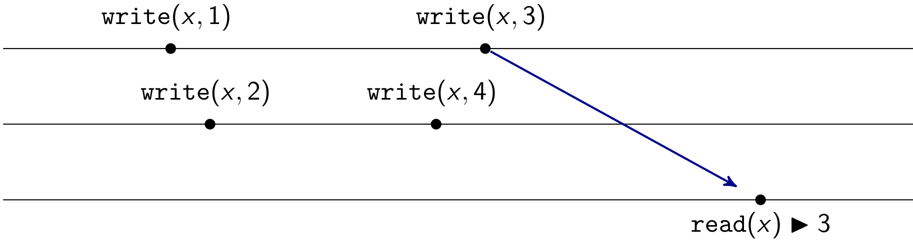
Data Independent Implementations

Observation: Written values do not influence behaviors.
⇒ We can assume written values are unique.



Data Independent Implementations

Observation: Written values do not influence behaviors.
$\Rightarrow$ We can assume written values are unique.



Unicity of writes implies a canonical **causality** relation (included in every other causality relation).

Bad Patterns to Characterize Violations

Bad pattern: set of operations related is a particular way

Bad Patterns to Characterize Violations

Bad pattern: set of operations related is a particular way

Defined using the following orders:

- *PO* (program order): connects operations from the same site

Bad Patterns to Characterize Violations

Bad pattern: set of operations related is a particular way

Defined using the following orders:

- *PO* (program order): connects operations from the same site
- *RF* (reads-from relation): connects `write` to `read`

Bad Patterns to Characterize Violations

Bad pattern: set of operations related is a particular way

Defined using the following orders:

- *PO* (program order): connects operations from the same site
- *RF* (reads-from relation): connects `write` to `read`
- *CO* (causal order): defined as $(PO \cup RF)^+$

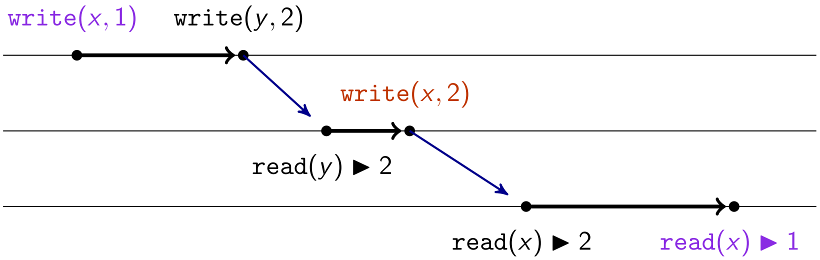
Bad Pattern for Causal Consistency: WriteCORead

- Two writes w_1 and w_2, and one read r_1 on the same variable:
  - r_1 reads-from w_1
  - $w_1 <_{CO} w_2 <_{CO} r_1$

Bad Pattern for Causal Consistency: WriteCORead

- Two writes w_1 and w_2, and one read r_1 on the same variable:
  - r_1 reads-from w_1
  - $w_1 <_{CO} w_2 <_{CO} r_1$

Example:



WriteCORead: Litmus tests

$w_1 <_{PO} w_2 <_{PO} r_1$:

$\texttt{write}(x, 1)$

$\texttt{write}(x, 2)$

$\texttt{read}(x) \blacktriangleright 1$

WriteCORead: Litmus tests

$w_1 <_{PO} w_2 <_{PO} r_1$:

write$(x, 1)$
write$(x, 2)$
read$(x) \blacktriangleright 1$

$w_1 <_{PO} w_2 <_{CO} r_1$:

write$(x, 1)$		read$(y) \blacktriangleright 3$
write$(x, 2)$	$\|\|$	read$(x) \blacktriangleright 1$
write$(y, 3)$		

WriteCORead: Litmus tests

$w_1 <_{PO} w_2 <_{PO} r_1$:

$\mathtt{write}(x,1)$
$\mathtt{write}(x,2)$
$\mathtt{read}(x) \blacktriangleright 1$

$w_1 <_{PO} w_2 <_{CO} r_1$:

$\mathtt{write}(x,1)$		$\mathtt{read}(y) \blacktriangleright 3$
$\mathtt{write}(x,2)$	$\|\|$	$\mathtt{read}(x) \blacktriangleright 1$
$\mathtt{write}(y,3)$		

$w_1 <_{CO} w_2 <_{PO} r_1$:

$\mathtt{write}(x,1)$		$\mathtt{read}(y) \blacktriangleright 3$
$\mathtt{write}(y,3)$	$\|\|$	$\mathtt{write}(x,2)$
		$\mathtt{read}(x) \blacktriangleright 1$

$w_1 <_{CO} w_2 <_{CO} r_1$:

$\mathtt{write}(x,1)$		$\mathtt{read}(y) \blacktriangleright 3$		$\mathtt{read}(z) \blacktriangleright 4$
$\mathtt{write}(y,3)$	$\|\|$	$\mathtt{write}(x,2)$	$\|\|$	$\mathtt{read}(x) \blacktriangleright 1$
		$\mathtt{write}(z,4)$		

Bad Patterns for Causal Consistency

- WriteCORead: two writes w_1 and w_2, and one read r_1 on some x s.t.
  - r_1 reads-from w_1
  - $w_1 <_{CO} w_2 <_{CO} r_1$
- CyclicCO: $CO = (PO \cup RF)^+$ is cyclic
- ThinAir: a read operation $r = \texttt{read}(x) \blacktriangleright v$ with $v \neq 0$ s.t.
  - $w \not<_{RF} r$ for every write w
- WriteCOInit: a read operation $r = \texttt{read}(x) \blacktriangleright 0$ s.t.
  - $w <_{CO} r$ for some write w on x

Bad Patterns for Causal Consistency Variants

Causal Consistency	Causal Memory	Causal Convergence
CyclicCO	CyclicCO	CyclicCO
WriteCOInitRead	WriteCOInitRead	WriteCOInitRead
ThinAirRead	ThinAirRead	ThinAirRead
WriteCORead	WriteCORead	WriteCORead
	WriteHBInitRead	CyclicCF
	CyclicHB	

Bad Patterns for Causal Consistency Variants

Causal Consistency	Causal Memory	Causal Convergence
CyclicCO	CyclicCO	CyclicCO
WriteCOInitRead	WriteCOInitRead	WriteCOInitRead
ThinAirRead	ThinAirRead	ThinAirRead
WriteCORead	WriteCORead	WriteCORead
	WriteHBInitRead	CyclicCF
	CyclicHB	

Theorem (Bad Patterns)

A trace doesn't satisfy the criterion **X** *iff it contains a* **bad pattern** *for* **X**.

Outline

- Definition(s) of **causal consistency**
- Characterize **all causal consistency violations** using bad patterns
- Using bad patterns for verifying data-independent implementations
  - Single-Trace Verification: **polynomial time**
  - **Bad patterns** can be recognized with **state machines**
  - **Generic reduction** from causal consistency to **reachability**
  - All-Traces Verification: **decidable**

Polynomial-Time Single-Trace Verification

Theorem (Single-Trace Verification)

Singe-Trace Verification of causal consistency is NP-**complete**.

Polynomial-Time Single-Trace Verification

Theorem (Single-Trace Verification)

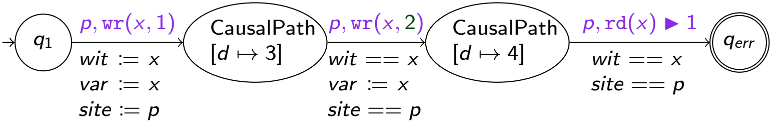
Singe-Trace Verification of causal consistency is NP-**complete**.

Theorem (Single-Trace Verification)

Singe-Trace Verification of causal consistency is **polynomial** *when* **writes are unique**.
(By checking the absence of bad patterns.)

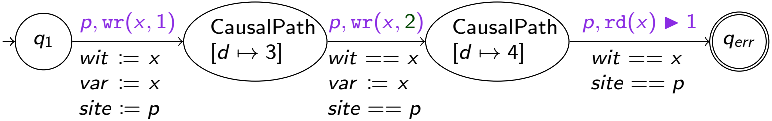
Recognizing Bad Patterns with Register Automata

- By data independence, we can use a bounded number of values
- Registers are needed to store variable names while tracking causality paths
- WriteCORead:

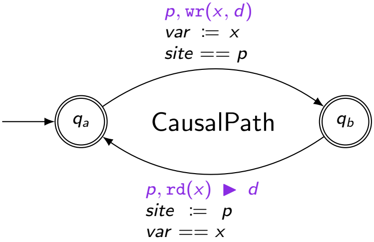


Recognizing Bad Patterns with Register Automata

- By data independence, we can use a bounded number of values
- Registers are needed to store variable names while tracking causality paths
- WriteCORead:

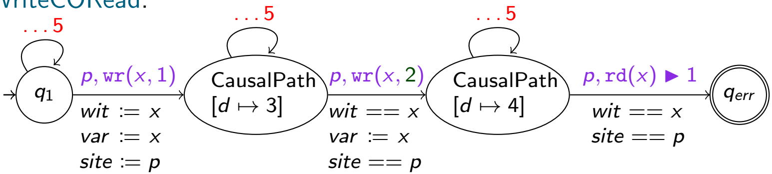


CausalPath tracks alternations of *PO* and *RF*

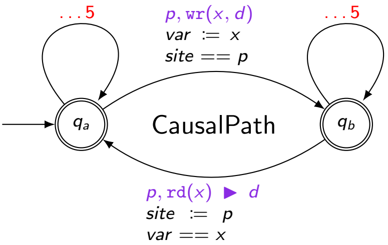


Recognizing Bad Patterns with Register Automata

- By data independence, we can use a bounded number of values
- Registers are needed to store variable names while tracking causality paths
- WriteCORead:



CausalPath tracks alternations of *PO* and *RF*



(PTime) Reduction to Reachability/Invariant Checking

Machine M tracking all bad patterns.

Theorem (Reduction to Reachability)

An implementation I is **causally consistent** *iff $I \times M$* **cannot** *reach an* **error state***.*

(PTime) Reduction to Reachability/Invariant Checking

Machine M tracking all bad patterns.

Theorem (Reduction to Reachability)

An implementation I is **causally consistent** *iff $I \times M$* **cannot** *reach an* **error state**.

- Holds for **any** data-independent implementation

(PTime) Reduction to Reachability/Invariant Checking

Machine M tracking all bad patterns.

Theorem (Reduction to Reachability)

An implementation I is ***causally consistent*** *iff $I \times M$* ***cannot*** *reach an* ***error state****.*

- Holds for **any** data-independent implementation
- Reuse of existing tools that solve **reachability**

(PTime) Reduction to Reachability/Invariant Checking

Machine M tracking all bad patterns.

Theorem (Reduction to Reachability)

An implementation I is ***causally consistent*** *iff $I \times M$* ***cannot*** *reach an* ***error state****.*

- Holds for **any** data-independent implementation
- Reuse of existing tools that solve **reachability**
- Manual or semi-automated proofs

All-Traces Verification

Setting: **Finite** number of **finite-state sites**.
(All traces are modelled by a finite-state automaton)

All-Traces Verification

Setting: **Finite** number of **finite-state sites**.
(All traces are modelled by a finite-state automaton)

Theorem (All-Traces Verification)

*Checking whether **all traces** of a finite-state implementation are causally consistent is **undecidable**.*

All-Traces Verification

Setting: **Finite** number of **finite-state sites**.
(All traces are modelled by a finite-state automaton)

Theorem (All-Traces Verification)

Checking whether **all traces** *of a finite-state implementation are causally consistent is* **undecidable***.*

Theorem (All-Traces Verification)

Checking whether **all traces** *of a* **data-independent** *finite-state implementation are causally consistent is* **decidable***.*

Summary and Future Work

Summary:

- Difficult to verify causal consistency in general
  (Single-Trace: NP-complete, All-Traces: Undecidable)

Summary and Future Work

Summary:

- Difficult to verify causal consistency in general
  (Single-Trace: NP-complete, All-Traces: Undecidable)
- **Bad patterns** for data-independent implementations

Summary and Future Work

Summary:

- Difficult to verify causal consistency in general
  (Single-Trace: NP-complete, All-Traces: Undecidable)
- **Bad patterns** for data-independent implementations
  - Single-Trace: PTime, All-Traces: Decidable

Summary and Future Work

Summary:

- Difficult to verify causal consistency in general
  (Single-Trace: NP-complete, All-Traces: Undecidable)
- **Bad patterns** for data-independent implementations
  - Single-Trace: PTime, All-Traces: Decidable
  - Polynomial-time reduction to **reachability**: approach for verifying causal consistency

Summary and Future Work

Summary:

- Difficult to verify causal consistency in general
  (Single-Trace: NP-complete, All-Traces: Undecidable)
- **Bad patterns** for data-independent implementations
  - Single-Trace: PTime, All-Traces: Decidable
  - Polynomial-time reduction to **reachability**: approach for verifying causal consistency

Future work:

- Bad patterns for **other criteria** (FIFO consistency, ...)
- for **other specifications** (Multi-Value Register, CRDTs, ...)

Summary and Future Work

Summary:

- Difficult to verify causal consistency in general
  (Single-Trace: NP-complete, All-Traces: Undecidable)
- **Bad patterns** for data-independent implementations
  - Single-Trace: PTime, All-Traces: Decidable
  - Polynomial-time reduction to **reachability**: approach for verifying causal consistency

Future work:

- Bad patterns for **other criteria** (FIFO consistency, ...)
- for **other specifications** (Multi-Value Register, CRDTs, ...)
- Application to existing **causally consistent systems** to prove their correctness
  (or find bugs)

Summary and Future Work

Summary:

- Difficult to verify causal consistency in general
  (Single-Trace: NP-complete, All-Traces: Undecidable)
- **Bad patterns** for data-independent implementations
  - Single-Trace: PTime, All-Traces: Decidable
  - Polynomial-time reduction to **reachability**: approach for verifying causal consistency

Future work:

- Bad patterns for **other criteria** (FIFO consistency, . . .)
- for **other specifications** (Multi-Value Register, CRDTs, . . .)
- Application to existing **causally consistent systems** to prove their correctness
  (or find bugs)

Thank you