Algorithmic Verification of Population Protocols

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Joint work with:
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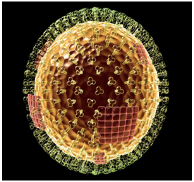
Monitoring Cows' Health



- Equip each cow in a heard with a sensor detecting influenza
- The sensor gives output 1

$$\begin{cases} 1, & \text{if the cow is infected} \\ 0, & \text{if it is not} \end{cases}$$

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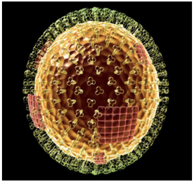

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- Question: Are there at least 5 infected cows?
- A solution:
  - The base station informs all agents to sense their environment
  - When 2 cows come close to each other their agents interact
  - The initiator takes the sum of the values and the responder takes 0
  - If a sum reaches 5 the output value 1 is propagated, otherwise forever remains 0

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Outstanding Properties of PPs

[AADFP '04]

The agents

- have constant memory (uniformity)
- do not have uids (anonymity)
- are passively mobile

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A Correct Population Protocol

- Input alphabet $X = \{0, 1\}$
- Output alphabet $Y = \{0, 1\}$
- Set of states $Q = \{q_0, q_1, \ldots, q_5\}$
- Input function $I : X \to Q$, defined as $I(\sigma) = q_\sigma$,
- Output function $O : Q \to Y$, defined as $O(q_5) = 1$ and $O(q) = 0$ for all $q \in Q - \{q_5\}$
- Transition function δ:

$$\begin{aligned}(q_i, q_j) &\to (q_{i+j}, q_0), \text{ if } i + j < 5 \\ &\to (q_5, q_5), \text{ otherwise}\end{aligned}$$

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The Code

	q_0	q_1	q_2	q_3	q_4	q_5
q_0	(q_0, q_0)	(q_1, q_0)	(q_2, q_0)	(q_3, q_0)	(q_4, q_0)	(q_5, q_5)
q_1	(q_1, q_0)	(q_2, q_0)	(q_3, q_0)	(q_4, q_0)	(q_5, q_5)	(q_5, q_5)
q_2	(q_2, q_0)	(q_3, q_0)	(q_4, q_0)	(q_5, q_5)	(q_5, q_5)	(q_5, q_5)
q_3	(q_3, q_0)	(q_4, q_0)	(q_5, q_5)	(q_5, q_5)	(q_5, q_5)	(q_5, q_5)
q_4	(q_4, q_0)	(q_5, q_5)	(q_5, q_5)	(q_5, q_5)	(q_5, q_5)	(q_5, q_5)
q_5	(q_5, q_5)	(q_5, q_5)	(q_5, q_5)	(q_5, q_5)	(q_5, q_5)	(q_5, q_5)

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	q_0	q_1	q_2	q_3	q_4	q_5
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q_1	(q_1, q_0)	(q_2, q_0)	(q_3, q_0)	(q_4, q_0)	(q_5, q_5)	(q_5, q_5)
q_2	(q_2, q_0)	(q_3, q_0)	(q_4, q_0)	(q_5, q_5)	(q_5, q_5)	(q_5, q_5)
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- 400 cows are all sick
- It is possible that 100 agents go to q_4 and the rest to q_0
- But now the farmer will never be alarmed of the problem (alarm state q_5 never appears)
- Interestingly, the protocol also has an erroneous computation for only 8 cows

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- We want to algorithmically verify our protocols in order to avoid such total or partial failures, particularly in critical applications

Problem (*GBPVER*)

Given a population protocol $\mathcal{A}$ for the basic model for which $Y_{\mathcal{A}} = \{0, 1\}$ and a first-order logical formula ϕ in Presburger arithmetic representing the specifications of $\mathcal{A}$ determine whether $\mathcal{A}$ conforms to ϕ.

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BPVER

- We mainly focus on the somewhat easier *BPVER* problem:
  - An integer $n \geq 2$ is also provided as part of the input
  - Here we want to determine whether $\mathcal{A}$ conforms to ϕ on K_n (complete communication digraph of n agents)
- Since a computation is infinite and there is a finite number of configurations, at least one configuration appears infinitely often
  - It is known [AADFP '06] that those configurations form a final strongly connected component of the transition graph $G(\mathcal{C}, E)$, where $\mathcal{C}$ is the set of all configurations and $(c, c') \in E$ iff $c \to c'$, e.g.

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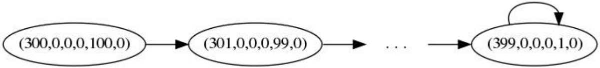

Figure: $(c_i)_{i=0,\ldots,5}$, c_i denotes the number of agents in state q_i

Another Typo

	q_0	q_1	q_2	q_3	q_4	q_5
q_0	(q_0, q_0)	(q_1, q_0)	(q_2, q_0)	(q_3, q_0)	(q_4, q_0)	(q_5, q_5)
q_1	(q_1, q_0)	(q_2, q_0)	(q_3, q_0)	(q_4, q_0)	(q_5, q_5)	(q_5, q_5)
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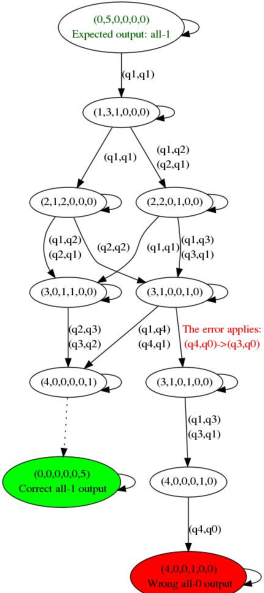
- It should be $(q_4, q_0) \to (q_4, q_0)$ instead, because now one counter is decreased without a reason

Another Typo: $(q_4, q_0) \rightarrow (q_3, q_0)$



Hardness of *BPVER*

Theorem

BPVER is coNP-hard*.*

- The reduction is from *HAMPATH* (directed)
- Given $\langle D, s, t \rangle$
- We construct a protocol $\mathcal{A}$ that does not conform to $(N_x < 0)$ on K_n iff D contains a directed hamiltonian path from s to t
- Also return $n = k - 1$, where $k = |V(D)|$
- The input alphabet X consists of the edges of D

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- Also return $n = k - 1$, where $k = |V(D)|$
- The input alphabet X consists of the edges of D

Hardness of *BPVER*

Theorem

BPVER is coNP-hard*.*

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- The protocol tries to verify whether its input assignment is a legal hamiltonian path
- If it encounters some violation, it rejects (otherwise, remains to an accepting output)
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  - If $D \notin HAMPATH$ then no input assignment is a hamiltonian path and the protocol conforms to ϕ (always finds some violation and rejects)
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Other Hardness Results

Theorem

GBPVER is coNP-hard.

- *BBPIVER* problem:
  - X is restricted to $\{0,1\}$
  - a specific input assignment is provided as part of the input
  - we ask whether the protocol is correct for that input assignment
- The bad news: even for this restricted version, hardness insists
- We can only hope for exponential-time algorithms that are efficient in practice
  - or for other interesting special cases that are efficiently solvable

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Protocol Correctness Criteria

1. $\phi(c) = -1$ for some $c \in C_I$
2. $\exists c, c' \in C_I$ such that $c \xrightarrow{*} c'$ and $\phi(c) \neq \phi(c')$
3. $\exists c \in C_I$ and $c' \in C_F$ such that $c \xrightarrow{*} c'$ and $O(c') = -1$
4. $\exists c \in C_I$ and $c' \in C_F$ such that $c \xrightarrow{*} c'$ and $\phi(c) \neq O(c')$
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Theorem (Complete Verifier)

Any algorithm checking criteria 1, 5, and 6 decides BPVER.

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An Exponential Algorithm for *BPVER*

- Find the reachable portion of the transition graph
  - To find the initial configurations we can use Fenichel's algorithm [1968] for finding the distributions of indistinguishable objects (agents) into distinguisable slots (initial states)
- Partition the induced graph into its strongly connected components by e.g. Tarjan's algorithm [1972]
- Replace each component with a node to obtain a dag
- Initial strongly connected component: contains at least one initial configuration
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- Final strongly connected component: has no outgoing edges
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- If there is a directed path from a x-initial component to a $|x-1|$-final component reject, otherwise accept
- An erroneous computation in the original graph begins from an initial configuration c expecting all-x output w.r.t. ϕ and leads to a final strongly connected component which contains a configuration that does not give the all-x output

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Conclusions

- Most natural verification problems concerning population protocols are coNP-hard
- There are easily checkable criteria for determining correctness
- Checking any of these defines a possibly non-complete verifier
- Checking 3 of these defines a complete verifier
- All of them are exponential since they are based on searching the transition graph
- We have implemented the first verification tool for population protocols
  - C++
  - Some non-complete and 1 complete verifier
- Experiments show that the running time can be greatly improved in the reject case if the transition graph is constructed on the fly

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- Can we avoid searching the huge transition graph by somehow looking inside the protocol?
- There is a constructive proof [AADFP '06] that a semilinear predicate is stably computable by the basic model
  - Unfortunately, there exists an unbounded number of correct protocols for the same predicate (we can simply add an unbounded number of dummy states and transitions)
  - e.g. replace $(q_0, q_1) \rightarrow (q_1, q_0)$ with

$$(q_0, q_1) \rightarrow (q_1, q_{d_1})$$
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Some Thoughts

- Can we somehow compare the default protocol (given by the constructive proof) with the provided one?
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Thank You!