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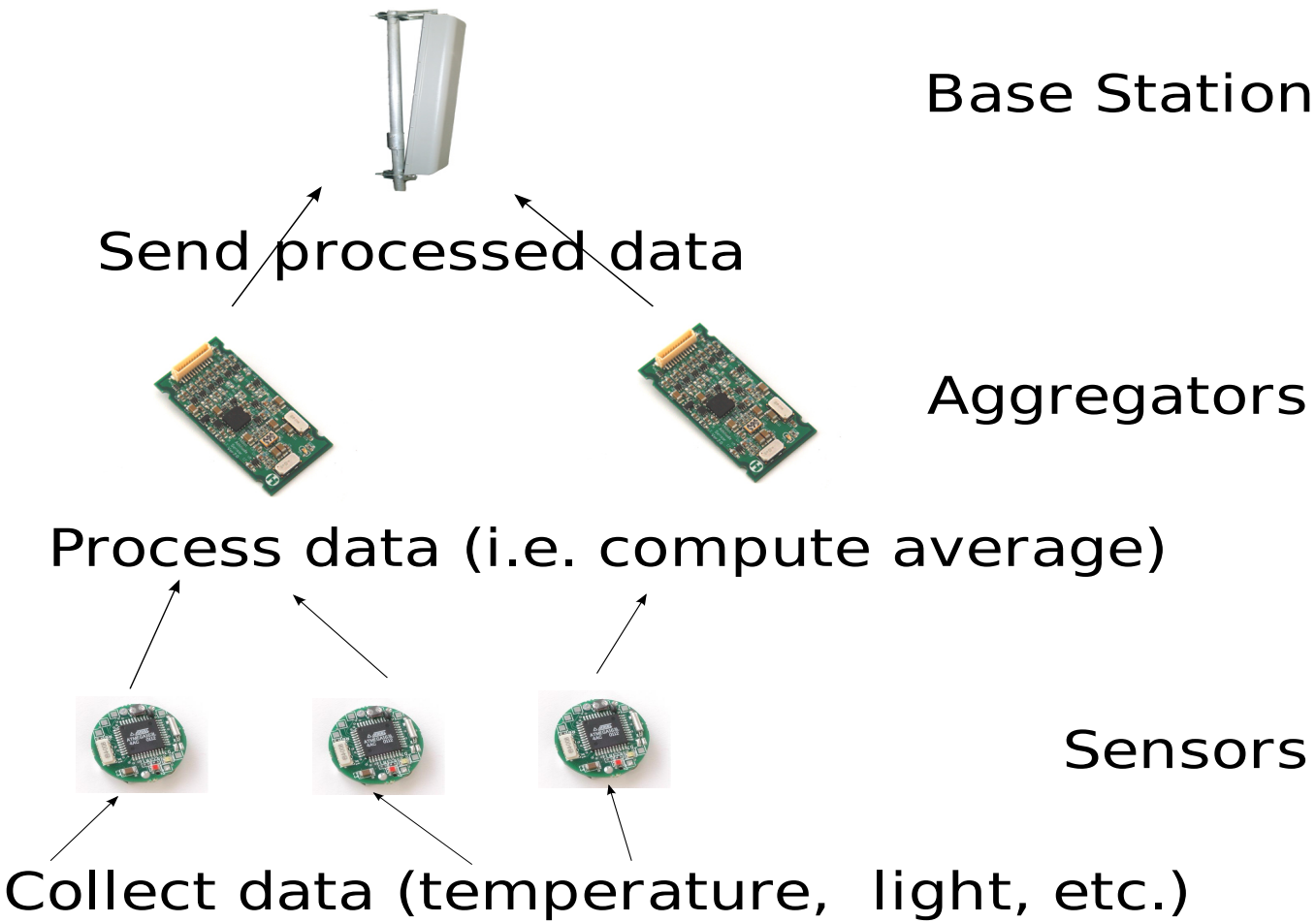
Automating Cut-off for Multi-Parameterized Systems

Midwest Verification Day 2010
To appear in the proceedings of the International Conference on Formal Engineering Methods (ICFEM 2010)

September 17, 2010

Sensor Network (Binary Tree)



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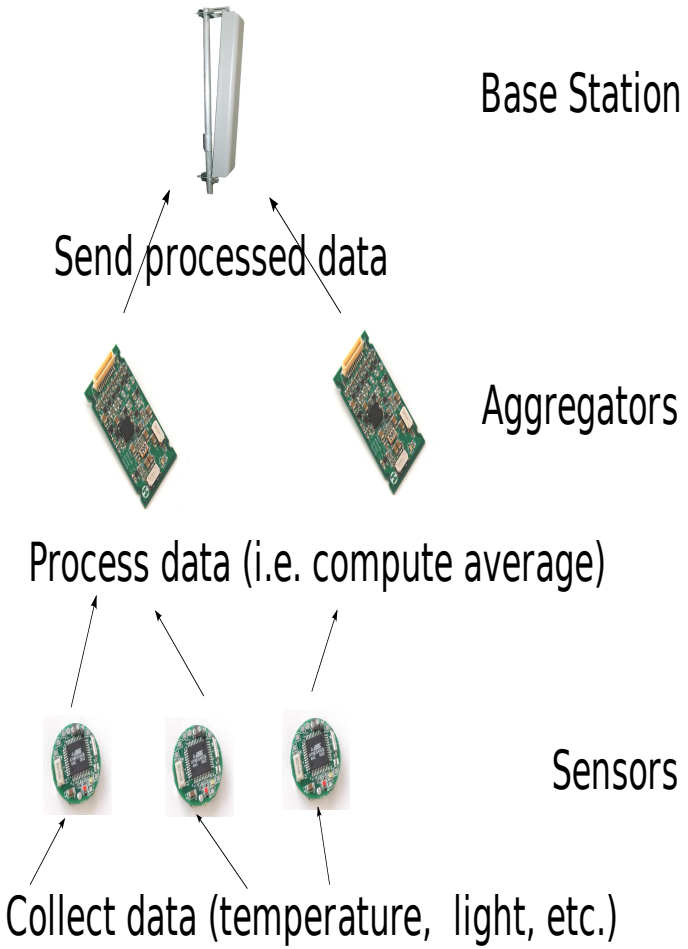

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  - ***m*** Aggregators
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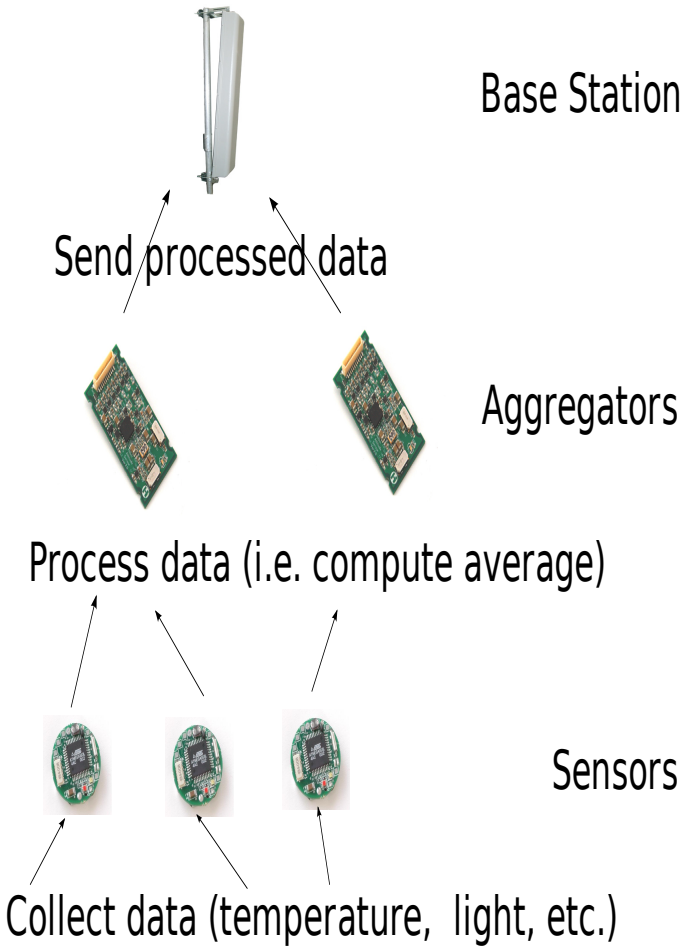

- In this system, there exists:
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- In this instance of the system:
  - $m = 2$
  - $n = 3$
- This system instance: $sys(2, 3)$

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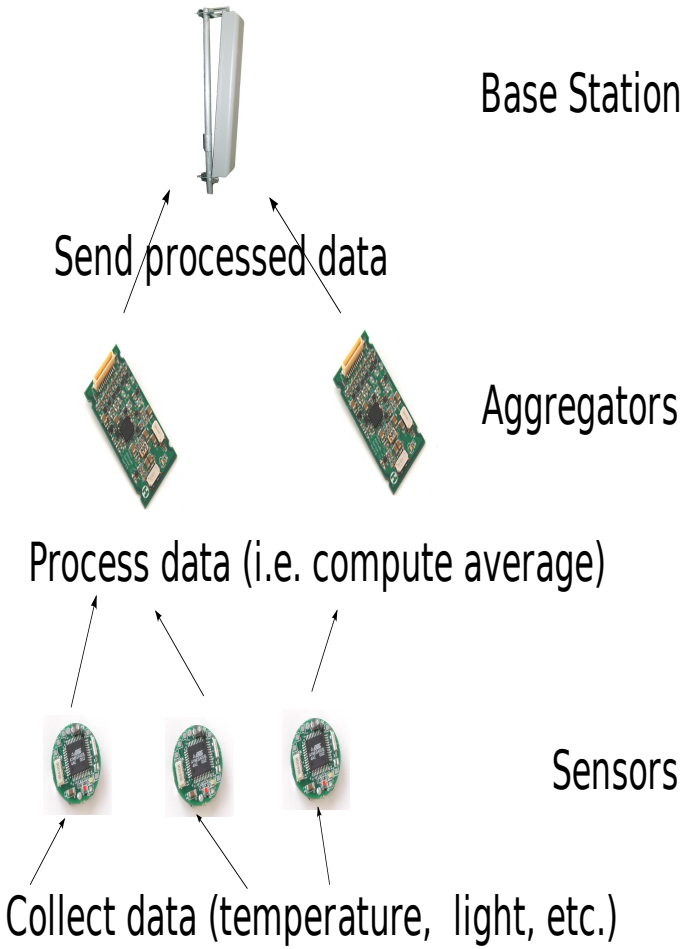

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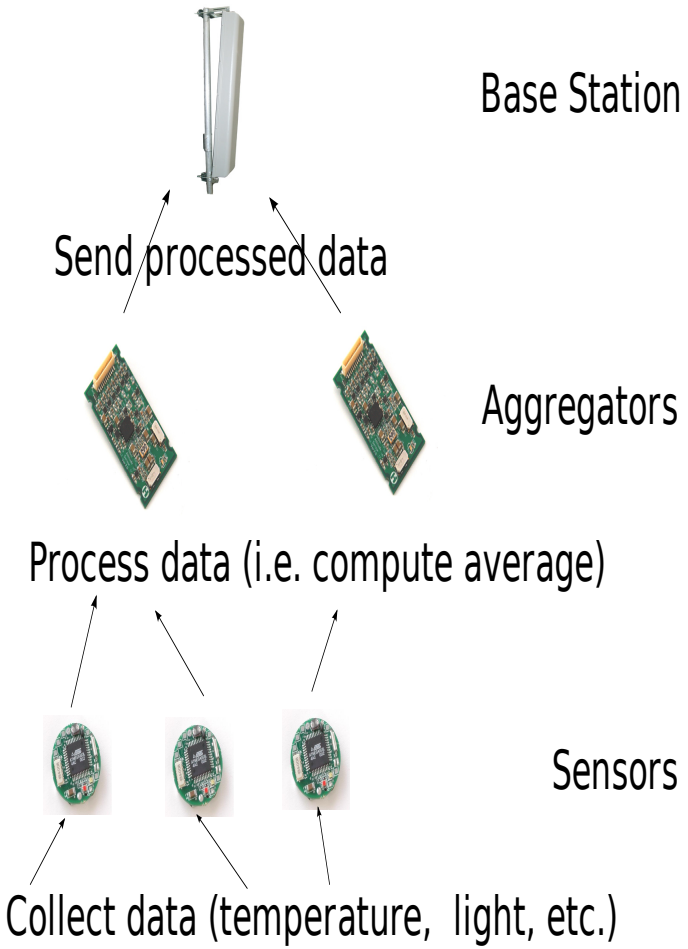

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  - m Aggregators
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- In this instance of the system:
  - $m = 2$
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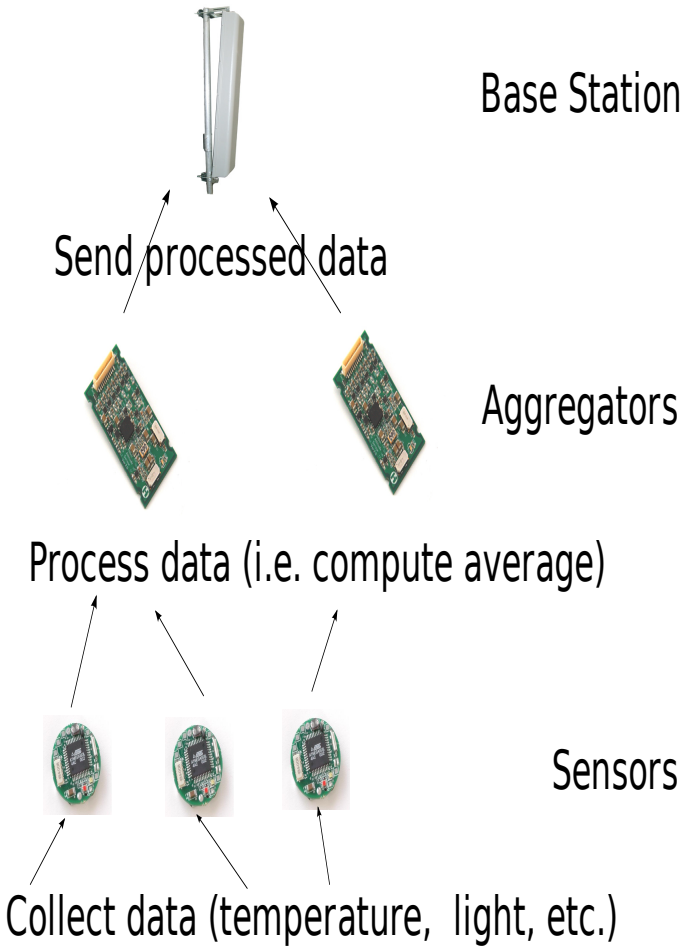
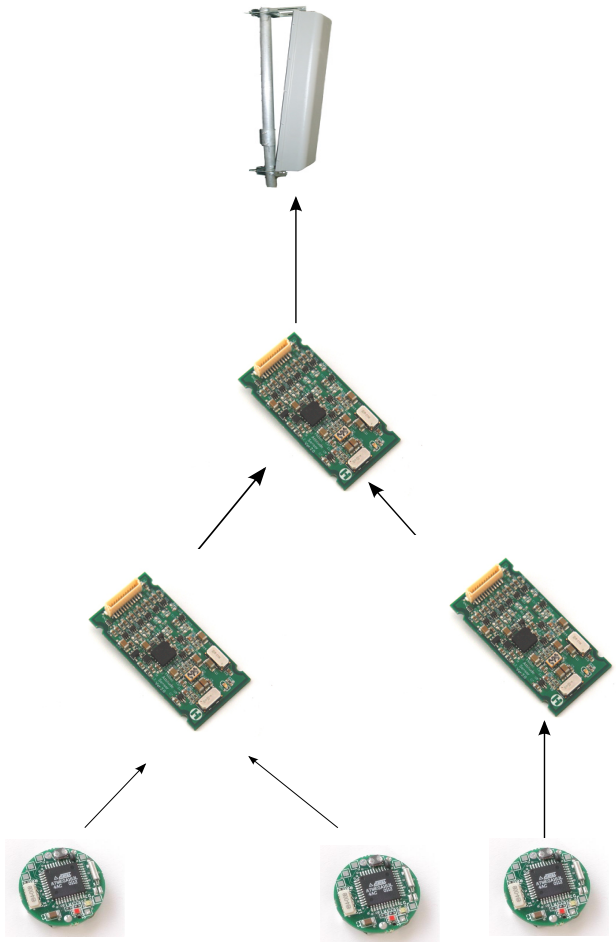
- This system instance: $sys(2, 3)$
- Two different process types.
- For every process type, there is a parameter.

Verifying a Property



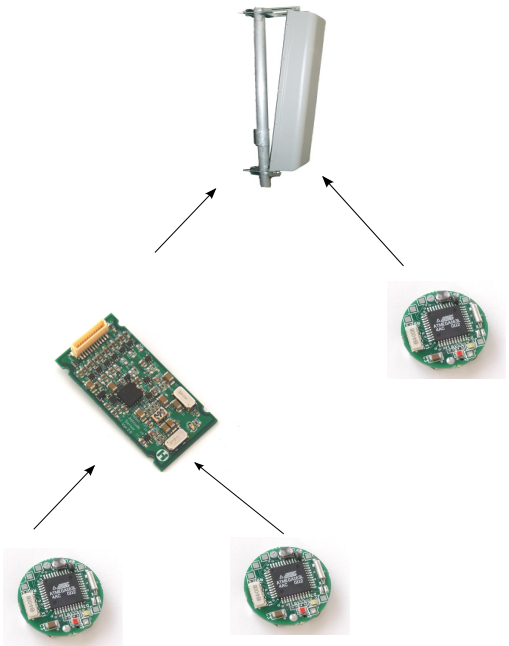
- Example property φ to verify:
  - Base station receives the average of all collected data.
- Which instance to verify?

Verifying a Property



$sys(3, 3)$

Verifying a Property



$sys(1, 3)$

Which Instance to Verify?

- If $\boldsymbol{sys(2,3)} \models \varphi$, will $\boldsymbol{sys(10,15)} \models \varphi$?

Which Instance to Verify?

- If $\boldsymbol{sys(2,3)} \models \varphi$, will $\boldsymbol{sys(10,15)} \models \varphi$?
- If $\boldsymbol{sys(m,n)} \models \varphi$, will $\boldsymbol{sys(m+1,n+1)} \models \varphi$?

Verifying Parameterized Systems

- **Problem of Verifying Multi-Parameterized Systems:**
  - Given a system $sys(n_1, n_2, \ldots, n_t)$ with t different types of processes, where n_i is the parameter for process type i,

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  - **is the property satisfied for *every* instance of the system?**
- For systems with only one parameterized process type (i.e. $sys(n)$), this is an undecidable problem! [1].

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Existing Work

- Large amount of existing work (mostly for **1** parameter)[2] [3].
- Key idea based on the notion of *cut-off*.
- Identify a number $\boldsymbol{k}$ s.t.

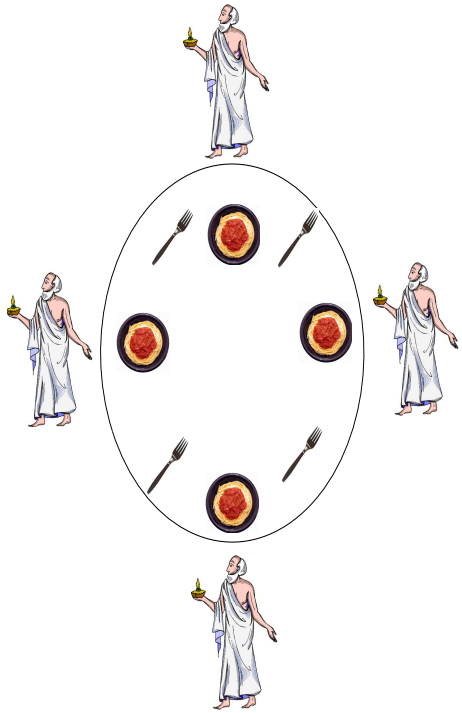
$$\boldsymbol{sys(k)} \models \varphi \Leftrightarrow \forall \boldsymbol{n} > \boldsymbol{k} : \boldsymbol{sys(n)} \models \varphi$$

- No need to verify properties for $\boldsymbol{n} > \boldsymbol{k}$
- $\boldsymbol{k}$ is called the *cut-off*

[2] E. A. Emerson, R. J. Trefler, and T. Wahl. Reducing model checking of the few to the one. In ICFEM, pp. 94-113, 2006.

[3] C. N. Ip and D. L. Dill. Verifying systems with replicated components in murφ. In CAV, pages 147-158, 1996.

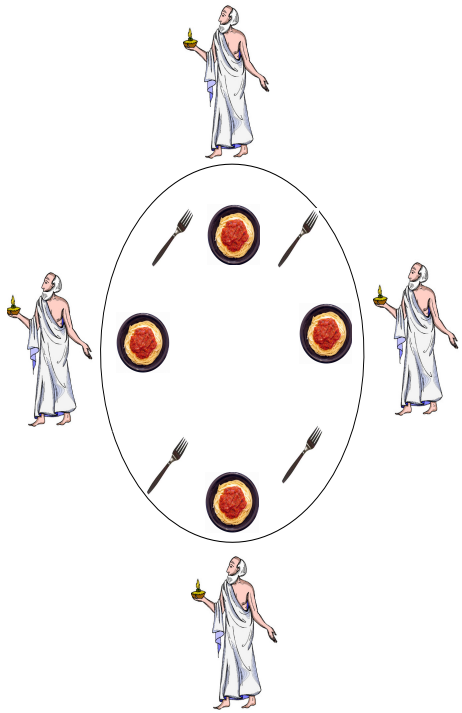
Cut-off for Single-parameterized Systems



Dining Philosopher

- Shared fork between every two philosophers
- Property φ: two neighbor philosophers cannot eat together

Cut-off for Single-parameterized Systems



φ: two neighbor philosophers cannot eat together

- Cut-off is **4** [Emerson and Cahlon TACAS 2002]
- We showed cut-off is **3** [Hanna, Y., Basu, S., and Rajan, H. ESEC/FSE 2009]

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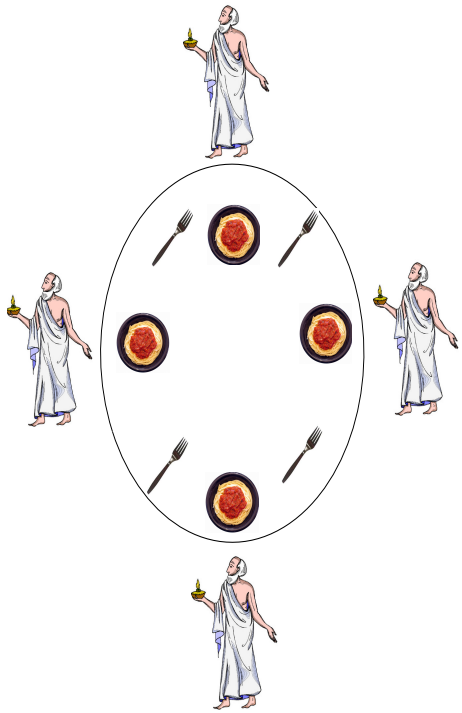

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- $\boldsymbol{sys(3)} \models \varphi \Leftrightarrow \forall \boldsymbol{n} > \mathbf{3}\ \boldsymbol{sys(n)} \models \varphi$

Problem with Existing Work

- Most ideas focus on a specific system with a single parameter

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Problem with Existing Work

- Most ideas focus on a specific system with a single parameter
  - [4] focuses on ring systems with a *single* parameter.
  - Not immediately applicable to new systems with
    - different topologies.
    - different number of parameters.
  - . . . without developing new theories from first principles.

[4] E. A. Emerson and K. S. Namjoshi. Reasoning about rings. In POPL, pages 85-94, 1995

Problem with Existing Work

- [5] is the first to consider parameterized systems with different types processes.

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Problem with Existing Work

- [5] is the first to consider parameterized systems with different types processes.
  - works only for specific systems where processes communicate through shared resources.

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Proposed Solution

A Language-based Technique for Cut-off Computation [6]

Technical Contributions:

A representation strategy to specify system as input,
which enables
a cut-off generation algorithm .

Key Benefits:

- Fully automated – Ease of verification.
- Topology and parameter independent – User Specified

[6] Hanna, Y., Basu, S., and Rajan, H.. Behavioral Automata Composition for Automatic Topology Independent Verification of Parameterized Systems. ESEC/FSE 2009

Key Idea

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   - all possible actions of a process for every process type.
   - system topology

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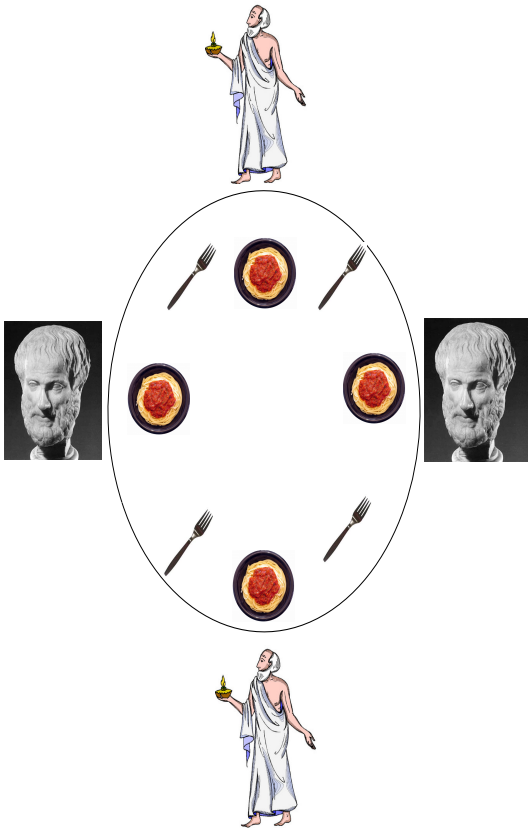
3. **Find**
   - the smallest system instance that allows such behaviors to happen, then **the size of this instance is the cut-off.**

- *Any larger system cannot exhibit any more behavior.*

Outline

- Multi-Parameterized System Definition
- Problem Statement
- **Solution:**
  - Define all possible actions of a process of every type.
  - Define system topology.
  - Generate maximal behavior a process of every type can induce in *any* environment.
  - Find smallest system allowing such behaviors to be exhibited.
- Case Studies

Right-Left Dining Philosophers (RLDP)



In Emerson and Cahlon
TACAS 2002

- Type “Left” phil.
  - Grab their left fork first
- Type “Right” phil.
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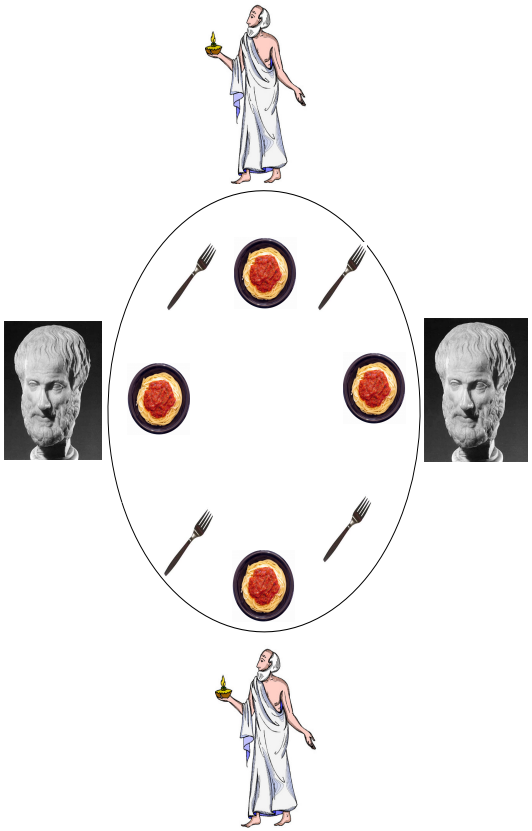

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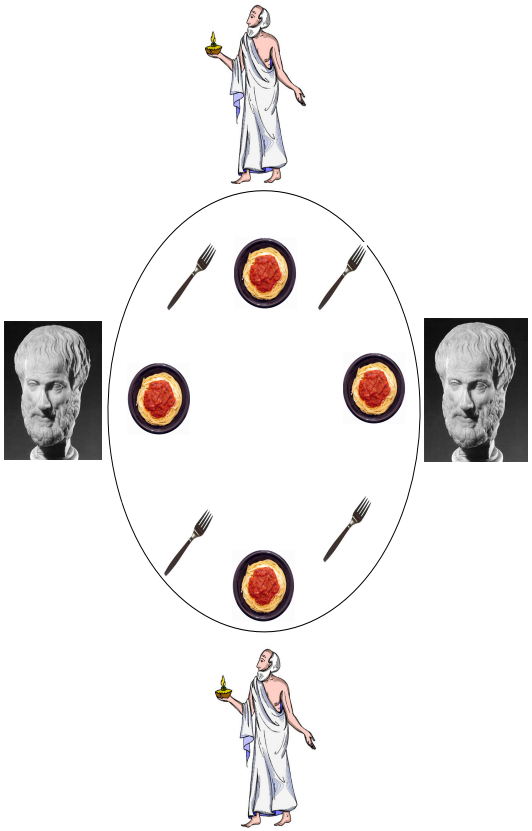

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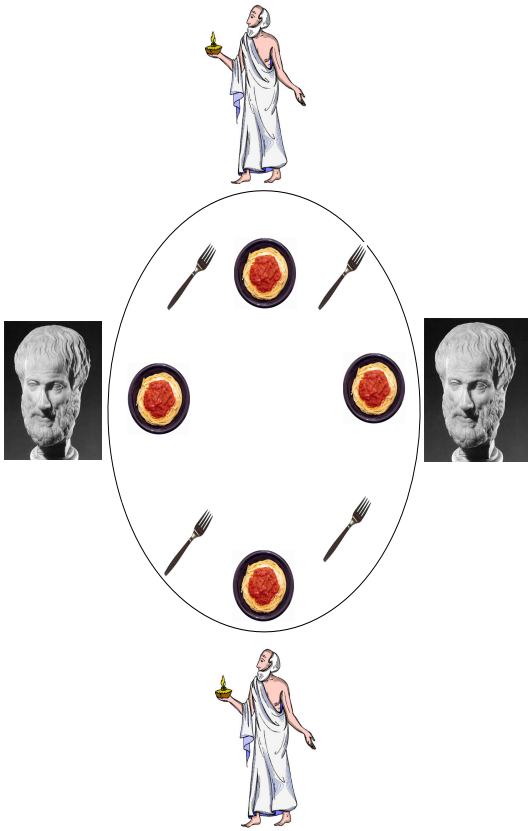

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- **Q: Which Instance to verify?**

Steps for Our Technique

1. **Define actions of a process of every type.**
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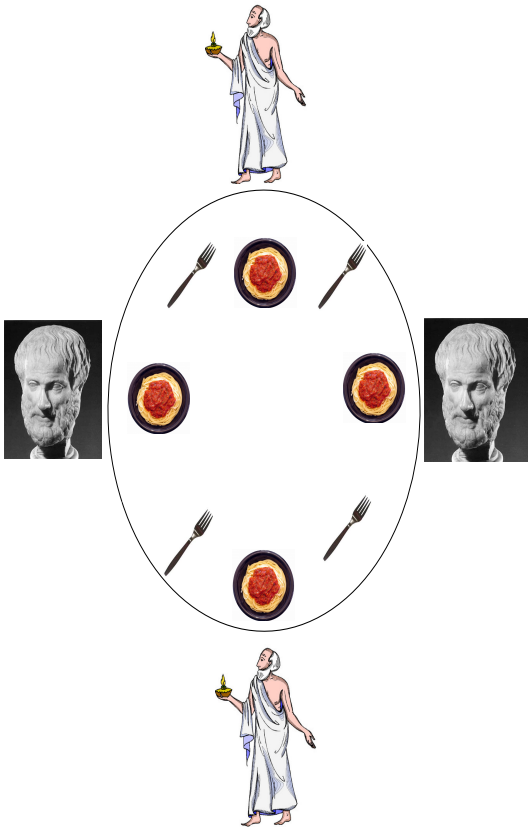
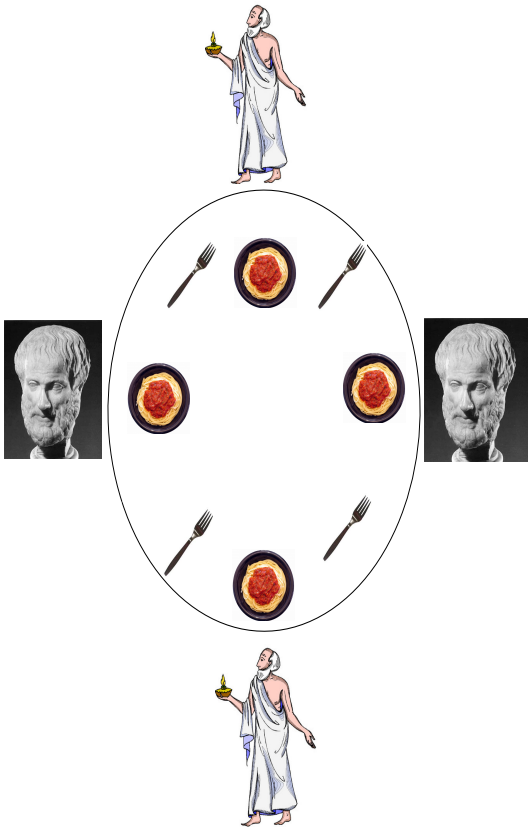
4. Find smallest system that exhibits *all* generated maximal behaviors.

“Left” Philosopher Actions



- **Send** request neighbor for left fork.

“Left” Philosopher Actions



- **Send** request neighbor for left fork.
- **Receive** approval to acquire left fork then **Send** request for right fork.

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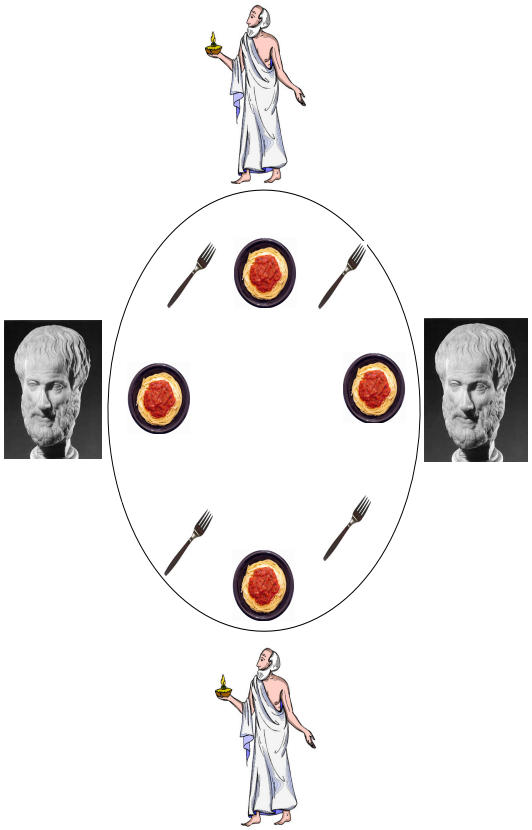

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- **Receive** rejection then **Send** another request.
- . . .

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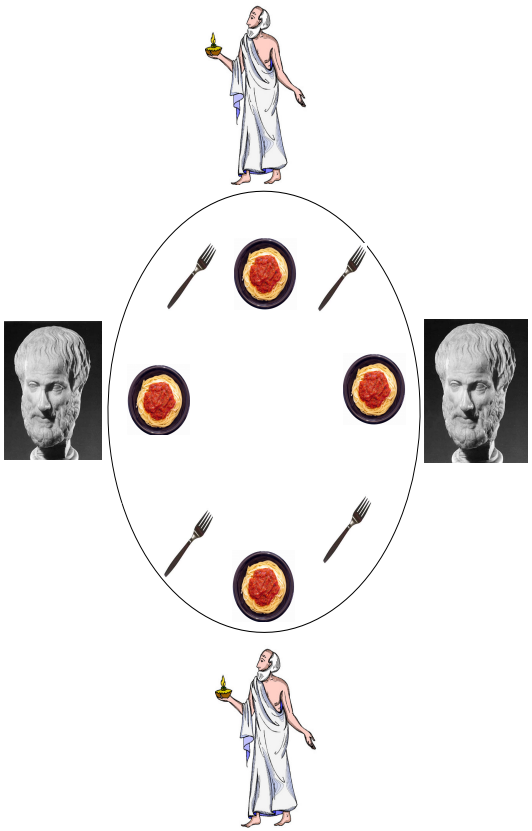

- **Send** request neighbor for left fork.
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- . . .

A similar set of actions exists for “Right” philosopher type (requesting right fork first)

“Left” Philosopher Actions as Behavioral Automata

1. **Send** request neighbor for left fork.

“Left” Philosopher Behavioral Automata

1. `L-ASKL: [neating, epsilon]->[waitl, askl2]`

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2. `L-ASK: [waitl, lfree] -> [waitr, askr2]`
3. `L-ReASKL: [waitl, ltaken] -> [waitl, askl2]`

   `...`

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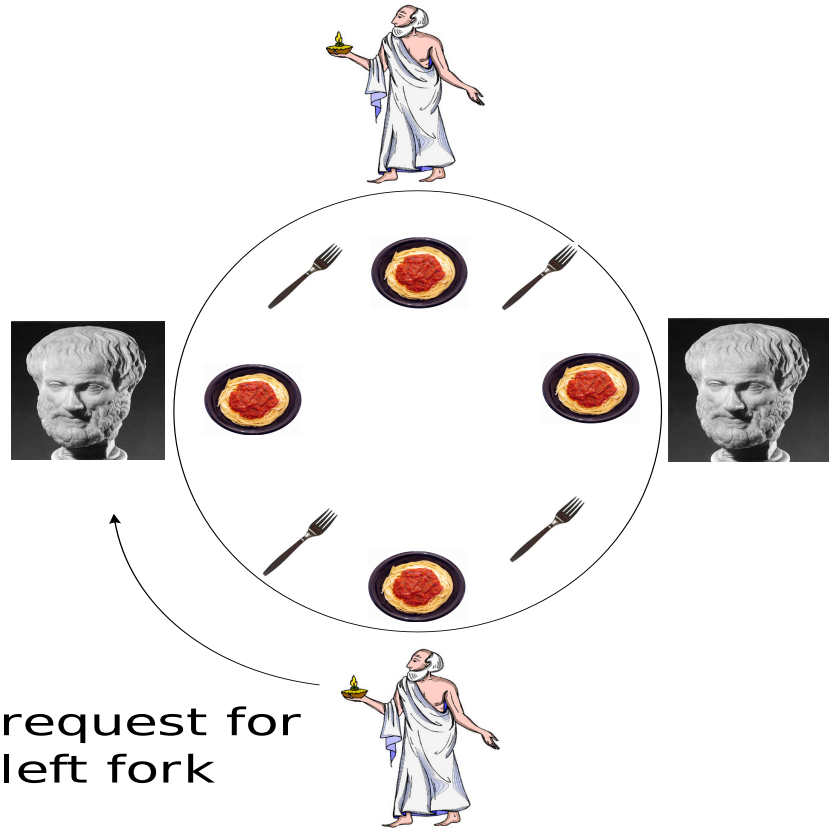
System Topology

Define how processes are connected together



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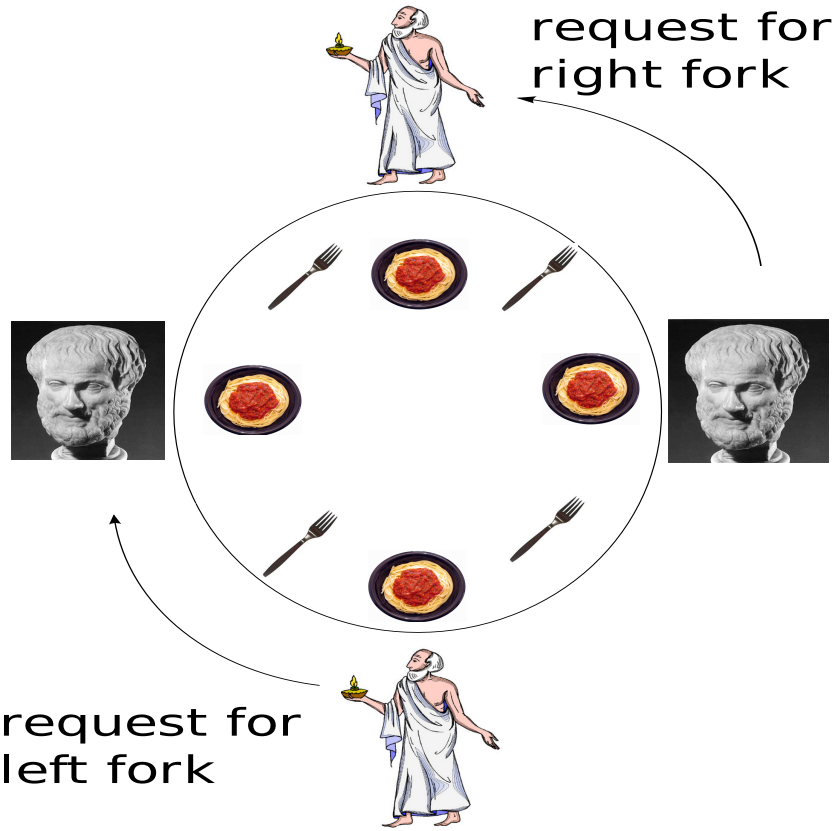

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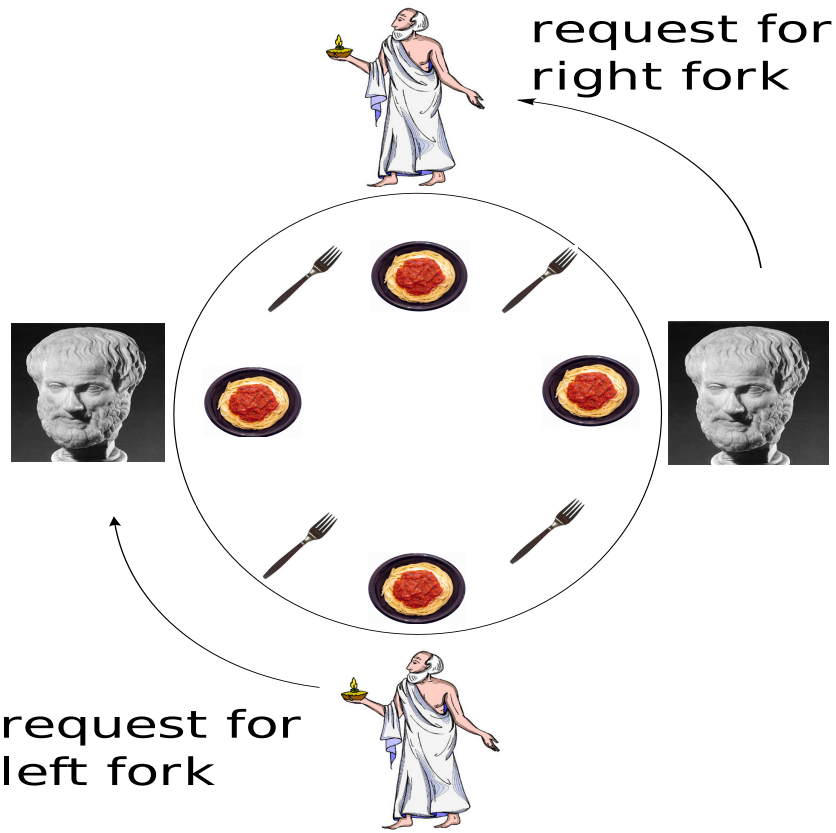

- Will connect processes in the form of a ring

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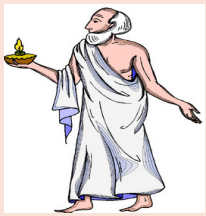
Maximal Behavior Induced by a “Left” Philosopher

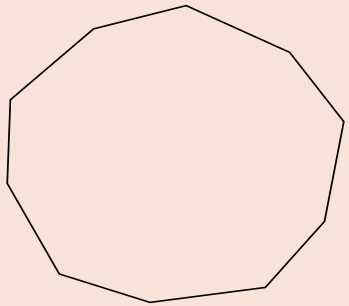
“Left” philosopher initial action

```
L-ASKL: [neating, epsilon] -> [waitl, askl2]
```

Maximal Behavior a “Left” philosopher can induce



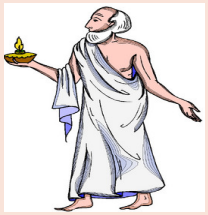
request
left fork



environment

Maximal Behavior Induced by a “Left” Philosopher

Maximal Behavior a “Left” philosopher can induce



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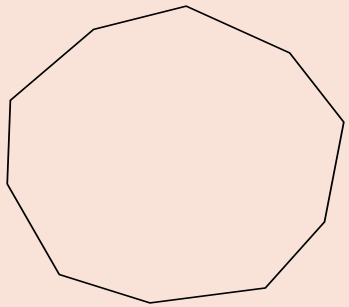

Q: What is the maximal behavior that can happen as a result of that request?

Maximal Behavior Induced by a “Left” Philosopher

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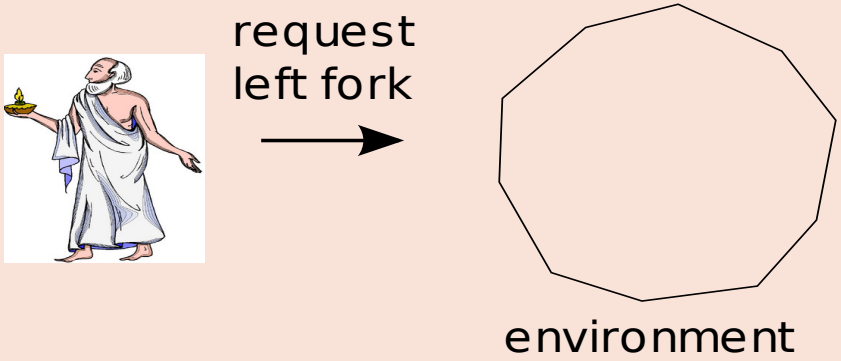


Q: What is the maximal behavior that can happen as a result of that request?

A: Check *all* actions that can respond to such request

Maximal Behavior Induced by a “Left” Philosopher

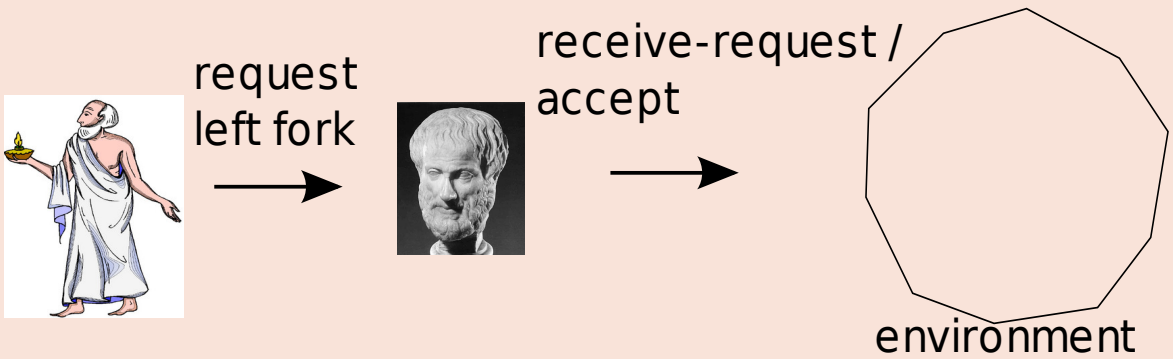
Maximal Behavior a “Left” philosopher can induce

```
L-ASKL: [neating, begin] -> [waitl, askl2]
```

“Right” Philosopher

```
R-FREEL-NE: [neating, askl2]->[neating, lfree]
```

Maximal Behavior a “Left” philosopher can induce



Maximal Behavior Induced by a “Left” Philosopher

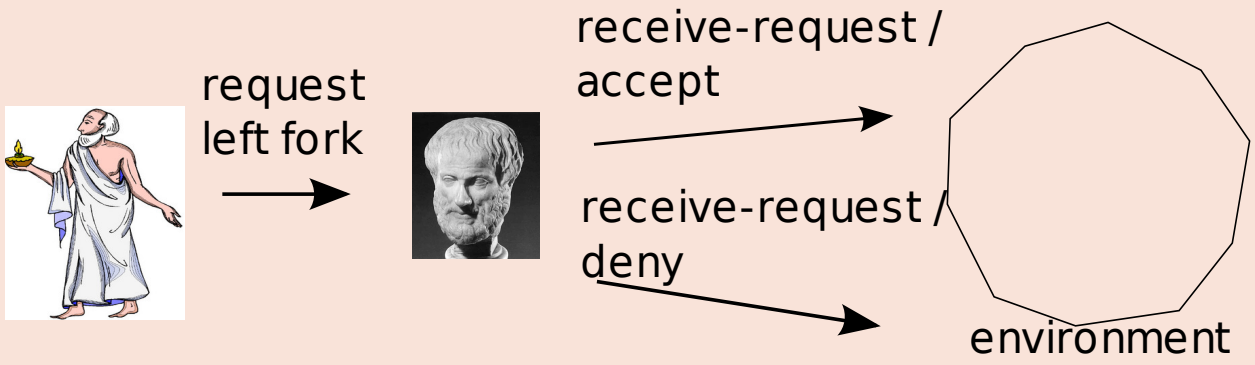
“Left” Philosopher

```
L-ASKL: [neating, epsilon] -> [waitl, askl2]
```

“Right” Philosopher

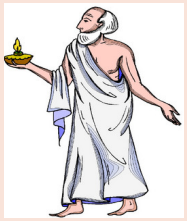
```
R-BUSYL-WR: [waitr, askl2] -> [waitr, ltaken]
```

Maximal Behavior a “Left” philosopher can induce

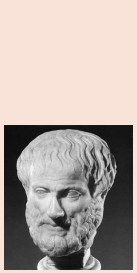


Maximal Behaviors in the RLDP Protocol

Maximal Behavior a “Left” philosopher can induce



Maximal Behavior a “Right” philosopher can induce



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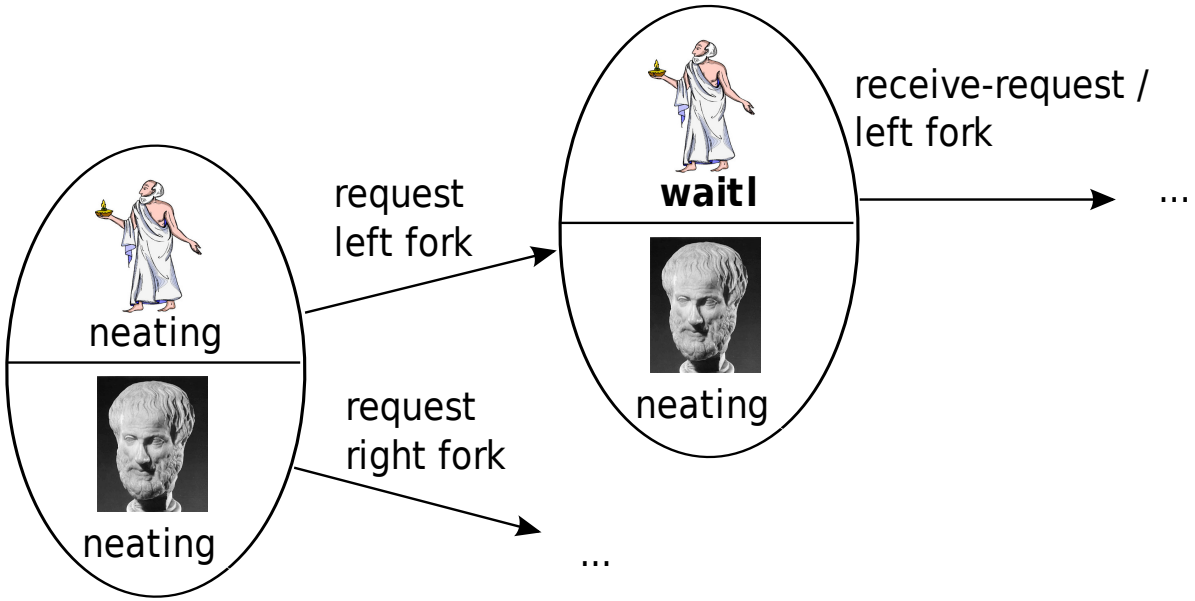
1. Define actions of a process.
2. Define system topology.
3. Generate maximal behavior a process of every type can generate in *any* environment.
4. **Find smallest system that exhibits *all* generated maximal behaviors.**

Goal of Finding Smallest System Instance

- Find the smallest instance that can exhibit all generated maximal behaviors. The size of this system instance $(k_1, k_2, \ldots, k_t)$ is the cut-off

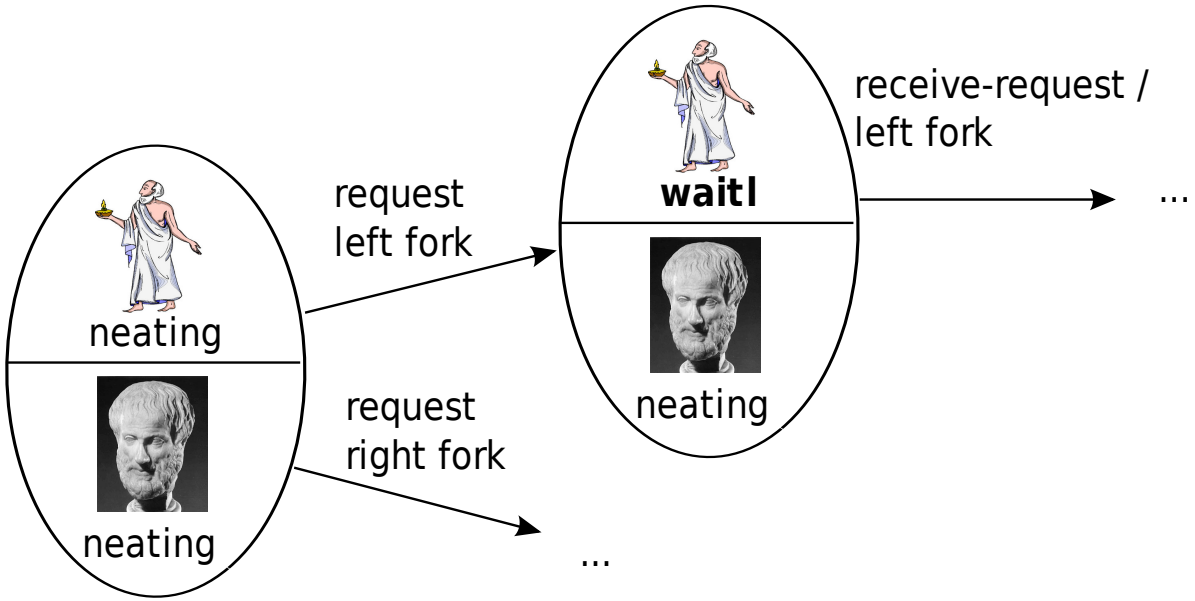
$sys(k_1, k_2, \ldots, k_t)$ satisfies $\varphi \Leftrightarrow$ All larger system instances satisfy φ

System with One Philosopher of Every Type



- **Goal:** The system should have all the sequence of paths in every generated maximal behavior.

System with One Philosopher of Every Type



- **Goal:** The system should have all the sequence of paths in every generated maximal behavior.
- $sys(1_l, 1_r)$ does not all the sequence of paths, it is not the cut-off

Cut-off for RLDP Protocol

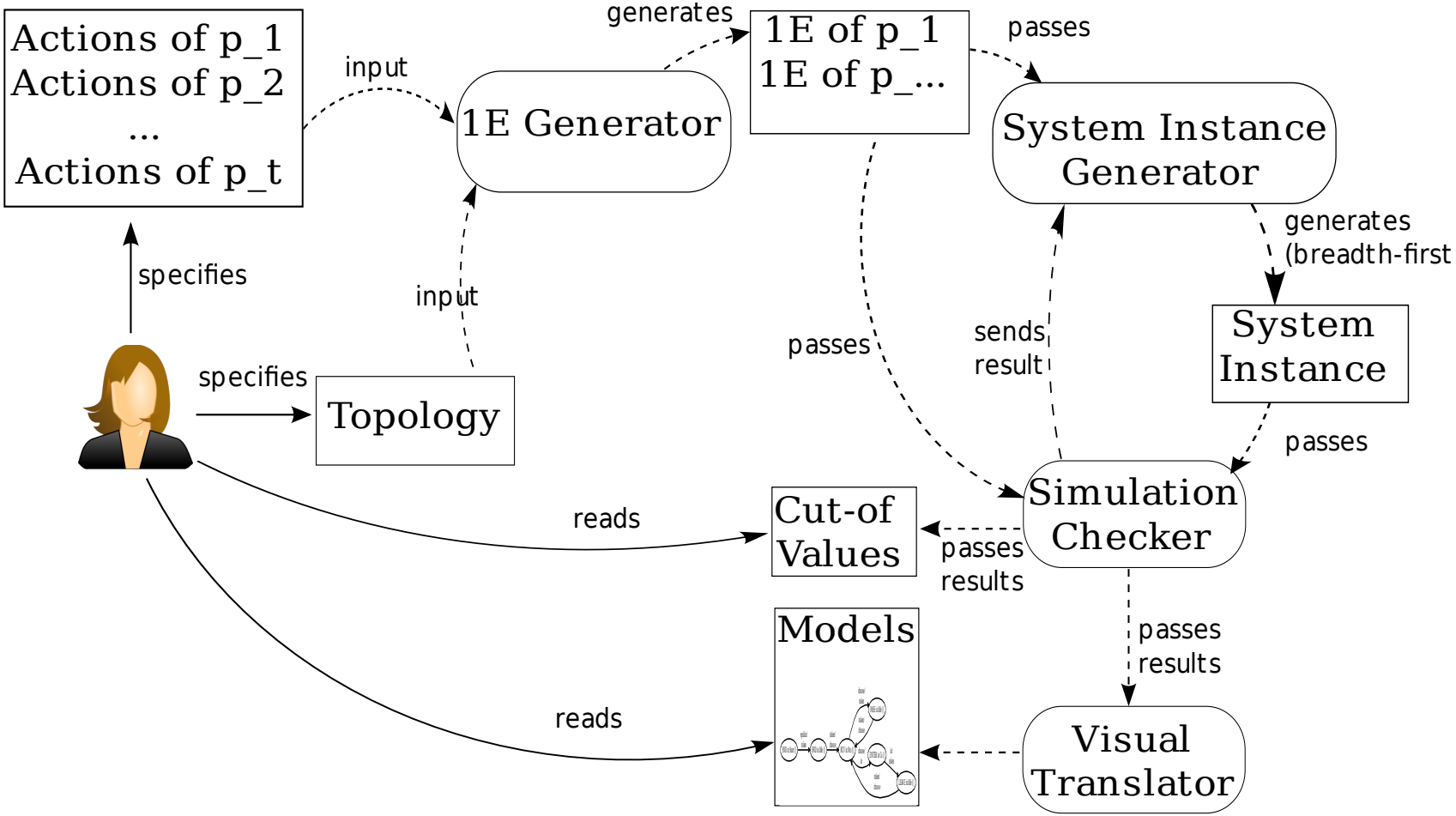
- A system with **3** philosophers of each type exhibits the maximal behaviors $1E_l$ and $1E_r$
- **cut-off for RLDP is $3_l, 3_r$**

***sys*$(3_l, 3_r)$** satisfies $\varphi \Leftrightarrow$ all larger system instances satisfy φ

Kind of Properties φ

- Properties involving one process i
- Properties involving 2 neigbor processes i, j
  - Could be of different types.

Our Tool: Golok



Comparison with Other Techniques

	Topology	Existing Work	Our Technique
		Cut-off	Cut-off
Dining Phil.	Ring	**4** *	**3**
RLDP	Ring	$\mathbf{2}_r, \mathbf{2}_l$ *	$\mathbf{3}_r, \mathbf{3}_l$
Spin Lock	Star	**3**‡	**2**
Spin Lock (Multiple Objects)	Star	X	$\mathbf{2}_t, \mathbf{2}_o$
Bounded-Buffer	Star	X	$\mathbf{2}_p, \mathbf{1}_c$

* E. A. Emerson and V. Kahlon. Model checking large-scale and parameterized resource allocation systems. In TACAS, pages 251-265, 2002.
‡ Basu, S., Ramakrishnan, C.R.: Compositional analysis for verification of parameterized systems. Theor. Comput. Sci. 2006

Conclusion

- Many systems are multi-parameterized thus comes the need to verify them.
- Reduce problem to verify small system with cut-off k.
- Current solutions are topology/parameters specific.
  - New theories required for every new system.
- **Our Solution:**
  - Automated technique for cut-off generation.
  - Topology/Parameter Independent.
- **Future Work:** Apply technique to
  - Infinite-domain data systems.

Questions?

http://www.cs.iastate.edu/~slede/golok/