Fault-Tolerant

# Model Checking A Self-Stabilizing Synchronization Protocol For Arbitrary Digraphs

**Mahyar R. Malekpour**

**http://shemesh.larc.nasa.gov/people/mrm/**

**DASC 2012, October 14 – 18**

# Outline

- Synchronization
- Verification via formal methods
- Fault spectrum and complexity
- Where are we now and where are we going?

# What Is Synchronization?

- Local oscillators/hardware clocks operate at slightly different rates, thus, they drift apart over time.
- Local logical clocks, i.e., timers/counters, may start at different initial values.
- The synchronization problem is to adjust the values of the local logical clocks so that nodes achieve synchronization and remain synchronized despite the drift of their local oscillators.

- Application – Wherever there is a distributed system
- How can we synchronize a distributed system?
- Under what conditions is it (im)possible?

# It for us all started with SPIDER, 1999

(Scalable Processor-Independent Design for Extended Reliability)

- Safety critical systems must deal with the presence of various faults, including arbitrary (Byzantine) faults

- **Goals (in the presence and absence of faults):**

1. Initialization from arbitrary state
2. Recovery from random, independent, transient failures
3. Recovery from massive correlated failures

# Why Is Synchronization Problem Difficult?

- Design of a fault-tolerant distributed real-time algorithm is extraordinarily hard and error-prone
  - Concurrent processes
  - Size and shape (topology) of the network
  - Interleaving concurrent events, timing, duration
  - Fault manifestation, timing, duration
  - Arbitrary state, initialization, system-wide upset

- It is notoriously difficult to design a formally verifiable solution for self-stabilizing distributed synchronization problem.

# Characteristics Of A Desired Solution

- Self-stabilizes in the presence of various failure scenarios.
  - From any initial random state
  - Tolerates bursts of random, independent, transient failures
  - Recovers from massive correlated failures
- Convergence
  - Deterministic
  - Bounded
  - Fast
- Low overhead
- Scalable
- No central clock or externally generated pulse used
- Does not require global diagnosis
  - Relies on local independent diagnosis
- A solution for $K = 3F+1$, if possible, otherwise, $K = 3F+1+X$, $(X = ?) \geq 0$

and,

must show the solution is correct.

# Formal Verification Methods

- Formal method techniques: **model checking**, **theorem proving**
- Use a model checker to verify a possible solution insuring that there are no false positives and false negatives.
  - It is deceptively simple and subject to abstractions and simplifications made in the verification process.
- Use a theorem prover to prove that the protocol is correct.
  - It requires a paper-and-pencil proof, at least a sketch of it.

# Model Checking

- Model checking issues
  - State space explosion problem
  - Tools require in-depth and inside knowledge, interfaces are not mature yet
  - Modeling a real-time system using a discrete event-based tool

- Intuitive solution is more memory and more computing power
  - PC with 4GB of memory running Linux, 32bit
  - There is a hardware limitation on the amount of memory that can be added to a given system
  - It may not eliminate/resolve state space problem

# Alternatively …

- Find a simpler solution
- Reduce the problem complexity by reducing its scope or restricting the assumptions
- Wait for a more powerful model checker
  - 64-bit tool utilizing more memory
  - Faster and more efficient model checking algorithm

# The Big Picture

- Solve the problem in the absence of faults.
- Learn and revisit faulty scenarios later on.

# Fault Spectrum

Simple fault classification:

1. None
2. Symmetric
3. Asymmetric (Byzantine)

The OTH (Omissive Transmissive Hybrid) fault model classification based on *Node Type* and *Link Type* outputs:
(http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100028297_2010031030.pdf)

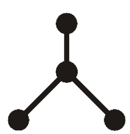
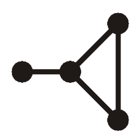
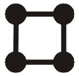
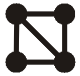
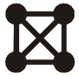
1. Correct (None)
2. Omissive Symmetric
3. Transmissive Symmetric (Symmetric)
4. Strictly Omissive Asymmetric
5. Single-Data Omissive Asymmetric
6. Transmissive Asymmetric (Byzantine)

# What About Topology?

- What should the graph look like?
  - Graphs of interest: single ring, double ring, grid, bi-partite, etc.
  - Possible options (Sloane numbers/sequence):

| *K* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Number of 1-connected graphs | 1 | 1 | 2 | 6 | 21 | 112 | 853 | 11117 |

  - Example, for 4 nodes there are 6 different graphs:

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Linear | Star/Hub | - | Ring | - | Complete |

# Sloane A001349

| n | a(n) |
|---|---|
| 0 | 1 |
| 1 | 1 |
| 2 | 1 |
| 3 | 2 |
| 4 | 6 |
| 5 | 21 |
| 6 | 112 |
| 7 | 853 |
| 8 | 11117 |
| 9 | 261080 |
| 10 | 11716571 |
| 11 | 1006700565 |
| 12 | 164059830476 |
| 13 | 50335907869219 |
| 14 | 29003487462848061 |
| 15 | 31397381142761241960 |
| 16 | 63969560113225176176277 |
| 17 | 245871831682084026519528568 |
| 18 | 1787331725248899088890200576580 |
| 19 | 24636021429399867655322650759681644 |

# Synchronization

- What are the parameters?
  - Maximum number of faults, $F \geq 0$
  - Communication delay, $D \geq 1$ clock ticks
  - Network imprecision, $d \geq 0$ clock ticks
    - So, communication delay is bounded by [$D$, $D+d$]
  - Oscillator drift, $0 \leq \rho << 1$,
  - Number of nodes, i.e., network size, $K \geq 1$
  - Synchronization period, $P$
  - Topology, $T$

Realizable Systems

Scalability

- **Synchronization, S = ($F$, $D$, $d$, $\rho$, $K$, $P$, $T$)**

# Where Are We Now?

- Have a family of solutions for detectably bad faults and $K \geq 1$ that applies to realizable systems.
  - Network impression and oscillator drift
- Have model checked a set of digraphs, NASA/TM-2011-217152
  - As much as our resources allowed (mainly, memory constrained)
  - Sample SMV codes are available at: http://shemesh.larc.nasa.gov/people/mrm/publication.htm
- Have a deductive proof, NASA/TM-2011-217184
  - Concise and elegant

# The Protocol

**Synchronizer:**

E0: if (*LocalTimer* < 0)
  *LocalTimer* := 0,

E1: elseif (*ValidSync()* and (*LocalTimer* < *D*))
  *LocalTimer* := $\gamma$,  *// interrupted*

E2: elseif ((*ValidSync()* and (*LocalTimer* $\geq T_S$))
  *LocalTimer* := $\gamma$,  *// interrupted*
  Transmit *Sync*,

E3: elseif (*LocalTimer* $\geq$ *P*)  *// timed out*
  *LocalTimer* := 0,
  Transmit *Sync*,

E4: else
  *LocalTimer* := *LocalTimer* + 1.

**Monitor:**

**case (message from the corresponding node)**
{Sync:
  ValidateMessage()
Other:
  Do nothing.
} // case

# How Does It Work?

1. If someone is out there – accept its ***Sync*** message and relay it to others,

2. If no one is out there (or they are too slow) – take charge and generate a new ***Sync*** message,

3. Ignore – reject all ***Sync*** messages while in the ***Ignore Window***.
   – Rules 1 and 2 result in an endless cycle of transmitting messages back and forth
   – The *Ignore Window* properly stops this endless cycle

# Key Results

## Global Lemmas And Theorems

How do we know when and if the system is stabilized?

- **Theorem *Convergence*** – *For all $t \geq C$, the network converges to a state where the guaranteed network precision is $\pi$, i.e., $\Delta_{Net}(t) \leq \pi$.*
- **Theorem *Closure*** – *For all $t \geq C$, a synchronized network where all nodes have converged to $\Delta_{Net}(t) \leq \pi$, shall remain within the synchronization precision $\pi$.*
- **Lemma *ConvergenceTime*** – *For $\rho \geq 0$, the convergence time is $C = C_{Init} + \lceil \Delta_{Init}/\gamma \rceil P$.*
- **Theorem *Liveness*** – *For all $t \geq C$, LocalTimer of every node sequentially takes on at least all integer values in $[\gamma, P-\pi]$.*

# Key Results

## Local Theorem

How does a node know when and if the system is stabilized?

- **Theorem *Congruence*** – *For all nodes $N_i$ and for all $t \geq C$, ($N_i$.LocalTimer(t) = γ) implies $\Delta_{Net}(t) \leq \pi$.*

## Key Aspects Of Our Deductive Proof

1. Independent of topology
2. Realizable systems, i.e., $d \geq 0$ and $0 \leq \rho << 1$
3. Continuous time

# Model Checking Propositions

- *SystemLiveness*

  *AF (ElapsedTime)*

- *ConvergenceAndClosure*

  *AF (ElapsedTime) ∧* -- *Determinism Property*

  *AG (ElapsedTime → AllWithinPrecision) ∧* -- *Convergence Property*

  *AG ((ElapsedTime ∧ AllWithinPrecision) →*

  *AX (ElapsedTime ∧ AllWithinPrecision))* -- *Closure Property*

- *Congruence*

  *AF (ElapsedTime) ∧*

  *AG ((ElapsedTime ∧ (Node_1.LocalTimer= g)) →*

  *AX (ElapsedTime ∧ AllWithinPrecision))*

# Model Checking Propositions (cont.)

- *ProtocolLiveness*

  *AF (ElapsedTime) ∧*

  *AG (((ElapsedTime) ∧ (Node_1.LocalTimer = i)) →*

  *AX ((Node_1.LocalTimer= i) | (Node_1.LocalTimer = i+1))) ∧*

  *AG (((ElapsedTime) ∧ (Node_1.LocalTimer = P)) →*

  *AX (Node_1.LocalTimer = 0))*

  *For all i = g .. (P - π)*

# Model Checked Cases

| *K* | **Topology** (all links bidirectional) | **Topology** (digraphs) |
|---|---|---|
| 2 | 1 of 1 | 1 of 1 |
| 3 | 2 of 2 | 5 of 5 |
| 4 | 6 of 6 | 83 of 83 |
| 5 | 21 of 21 | Single Directed Ring<br>2 Variations of<br>Doubly Connected<br>Directed Ring |
| 6 | 112 of 112 | - |
| 7 | Linear* | Linear* |
| 7 | Star* | Star* |
| 7 | Fully Connected* | Fully Connected* |
| 7 (3×4) | Fully Connected Bipartite* | Fully Connected Bipartite* |
| 7 | Combo | 4 of 4 |
| 7 | Grid | - |
| 7 | Full Grid | - |
| 9 (3×3) | Grid | - |
| 15 | Star* | Star* |
| 20 | Star* | Star* |

# More Results, In Retrospect

- Our family of solutions handles more than the no-fault (correct) case. It handles cases 1, 2, and 4 of the OTH fault classification. I.e., it is a fault-tolerant protocol as long as our assumptions are not violated and the faulty behavior does not violate our definition of digraph.
- In retrospect, "fault-tolerant" should be included in the paper's title.
- Our family of solutions is an emergent system.

The OTH (Omissive Transmissive Hybrid) fault model classification based on *Node Type* and *Link Type* outputs:

1. Correct (None, No-fault)
2. Omissive Symmetric (Fail-detected, Fail-silent)
3. Transmissive Symmetric (Symmetric)
4. Strictly Omissive Asymmetric (1 or 2)
5. Single-Data Omissive Asymmetric
6. Transmissive Asymmetric (Byzantine)

# Questions?