# Model-Driven Verifying Compilation of Synchronous Distributed Applications

Sagar Chaki, James Edmondson
October 1, 2014

MODELS'14, Valencia, Spain

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**01 OCT 2014** | 2. REPORT TYPE<br>**N/A** | 3. DATES COVERED<br>**-** |
| 4. TITLE AND SUBTITLE<br>**Model-Driven Verifying Compilation of Synchronous Distributed Applications** | | 5a. CONTRACT NUMBER<br>5b. GRANT NUMBER<br>5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S)<br>**Sagar Chaki James Edmondson** | | 5d. PROJECT NUMBER<br>5e. TASK NUMBER<br>5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Software Engineering Institute Carnegie Mellon University Pittsburgh, PA 15213** | | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | 10. SPONSOR/MONITOR’S ACRONYM(S)<br>11. SPONSOR/MONITOR’S REPORT NUMBER(S) |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br>**Approved for public release, distribution unlimited** | | |
| 13. SUPPLEMENTARY NOTES<br>**The original document contains color images.** | | |
| 14. ABSTRACT | | |
| 15. SUBJECT TERMS | | |

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | |
| **unclassified** | **unclassified** | **unclassified** | **SAR** | **24** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

# Outline

- Motivation
- Approach
- Sequentialization : SEQSEM & SEQDBL
- Examples
- Experimental Results
- Synchronizer Protocol : 2BSYNC
- Tool Overview & Demo
- Future Work

# Motivation

Distributed algorithms have always been important

- File Systems, Resource Allocation, Internet, …

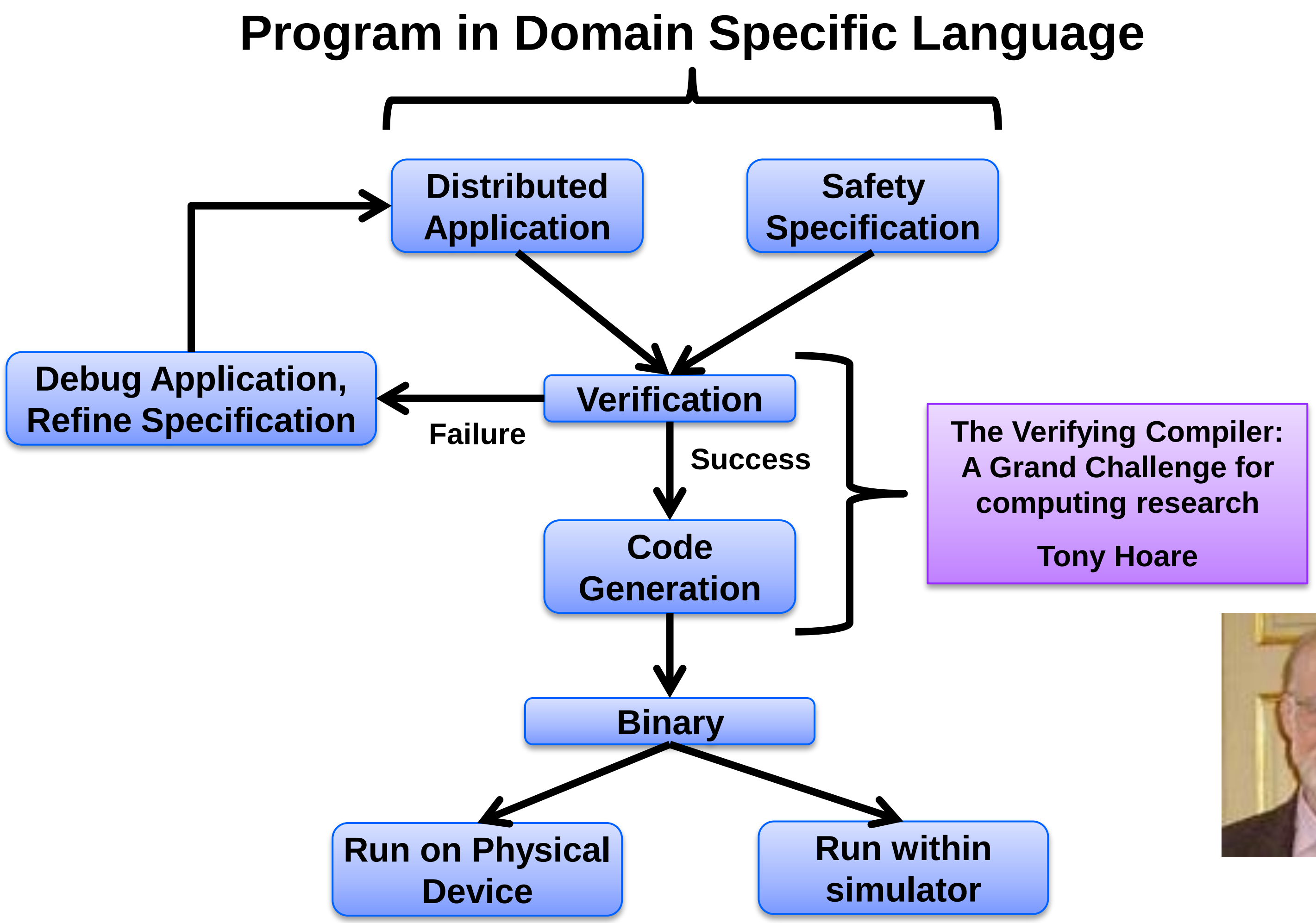
Increasingly becoming safety-critical

- Robotic, transportation, energy, medical

Prove correctness of distributed algorithm implementations

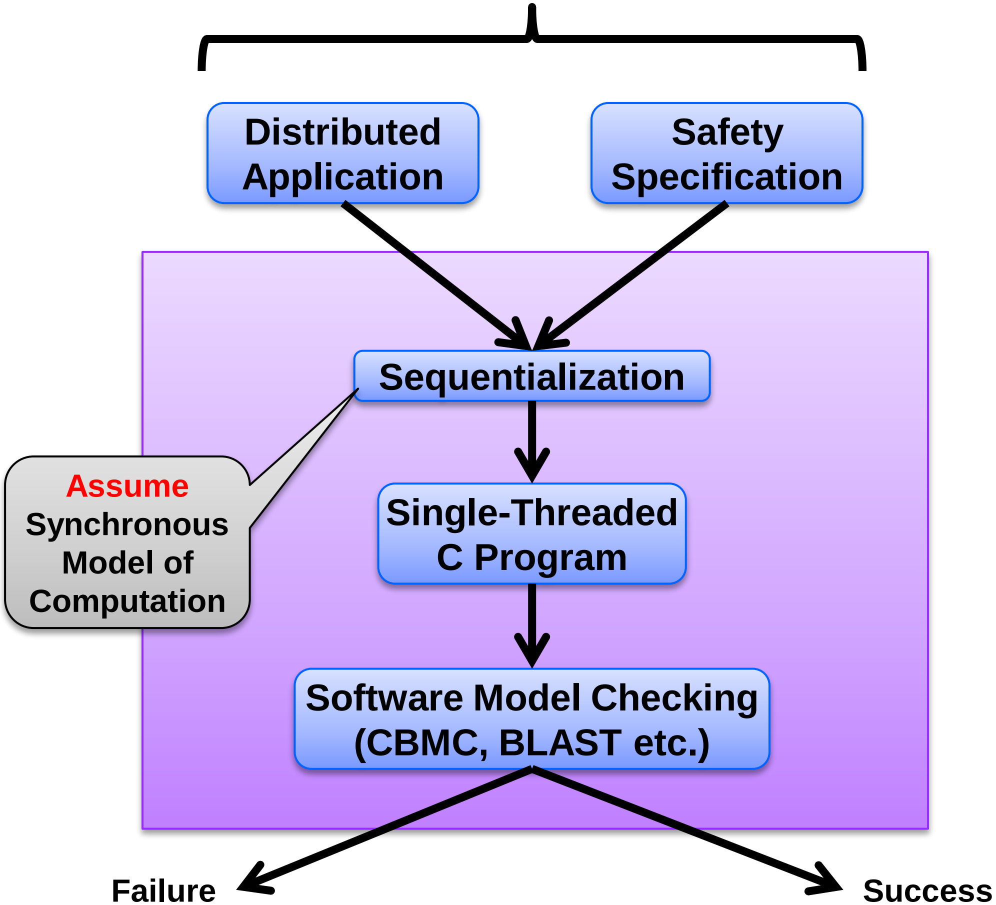
- Pseudo-code is verified manually (semantic gap)
- Implementations are heavily tested (low coverage)

# Approach : Verification + Code Generation

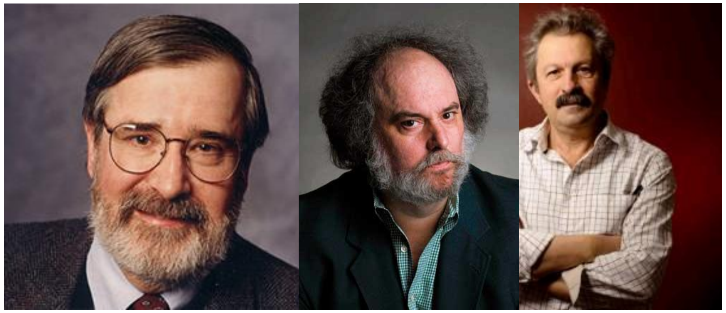



# Verification

## Program in Domain Specific Language




## Model Checking



Automatic verification technique for finite state concurrent systems.

- Developed independently by Clarke and Emerson and by Queille and Sifakis in early 1980's.
- ACM Turing Award 2007

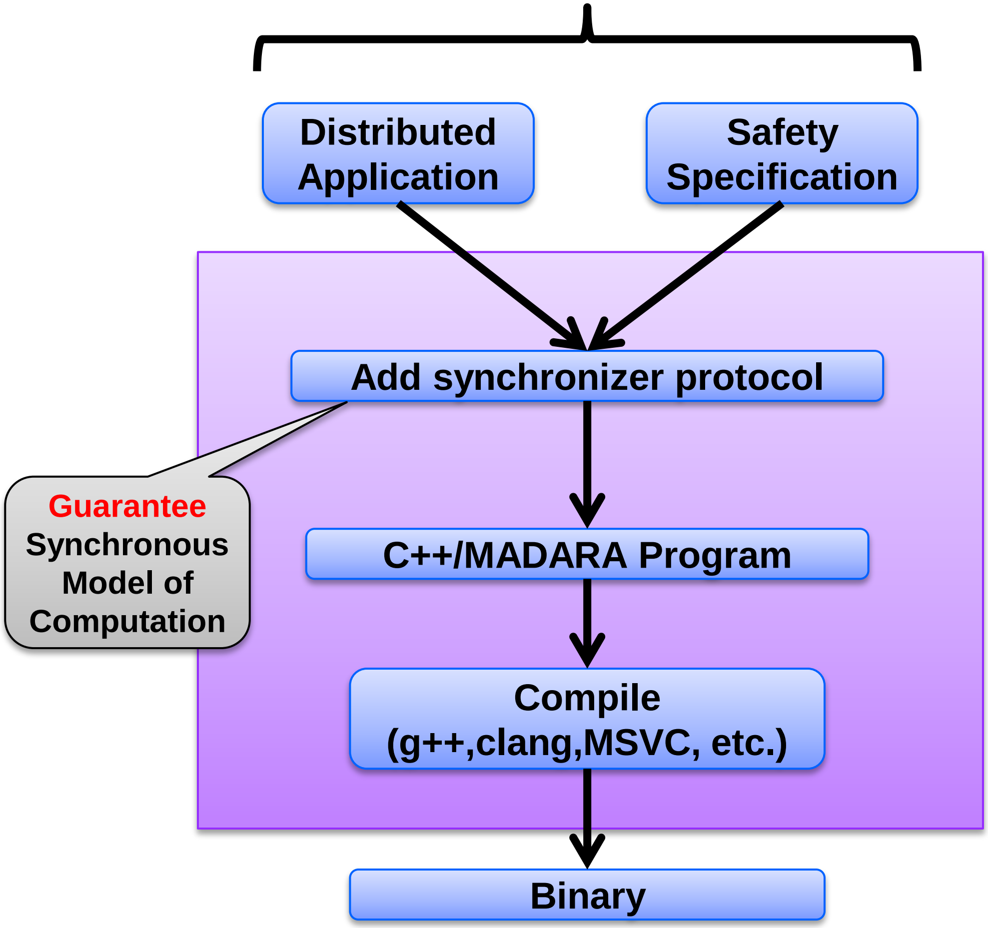
Specifications are written in propositional temporal logic. (Pnueli 77)

- Computation Tree Logic (CTL), Linear Temporal Logic (LTL), …

Verification procedure is an intelligent exhaustive search of the state space of the design

# Code Generation

## Program in Domain Specific Language




## MADARA Middleware

A database of facts: $DB = Var \mapsto Value$

Node $i$ has a local copy: $DB_i$

- update $DB_i$ arbitrarily
- publish new variable mappings
  - Immediate or delayed
  - Multiple variable mappings transmitted atomically

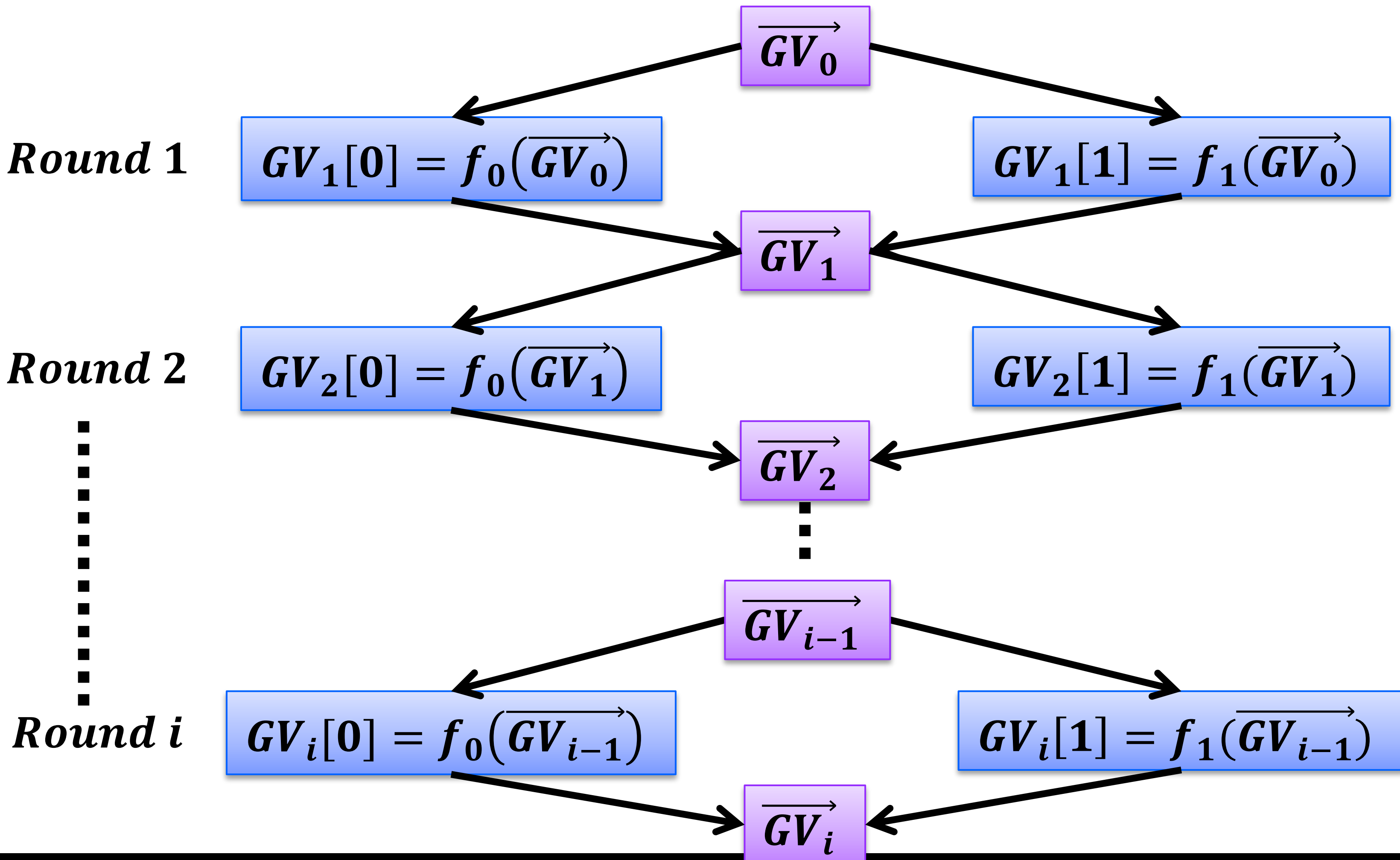
Implicit "receive" thread on each node

- Receives and processes variable updates from other nodes
- Updates ordered via Lamport clocks

Portable to different OSes (Windows, Linux, Android etc.) and networking technology (TCP/IP, UDP, DDS etc.)

# Synchronous Distributed Application (SDA)

**Node 0** $= f_0()$ **Shared Variables:** $\overrightarrow{GV} = GV[0], GV[1]$ **Node 1** $= f_1()$



# SDA Verification

Program with $n$ nodes : $P(n)$

- Each node has a distinct $id \in [1, n]$
- Array $GV$ has $n$ elements, $GV[i]$ writable only by node with id $i$
- Each element of $GV$ is drawn from a finite domain

In each round, node with id $id$ executes function $\rho$ whose body is a statement

$$
\begin{array}{lll}
stmt \coloneqq skip \mid lval = exp & & (assignment) \\
\quad \mid ITE(exp, stmt, stmt) & & (if, then, else) \\
\quad \mid ALL(IV, stmt) & & (iterate\ over\ nodes : use\ to\ check\ existence) \\
\quad \mid \langle stmt^{+} \rangle & & (iteration\ of\ statements) \\
lval \coloneqq GV[id][w] & & (lvalues) \\
exp \coloneqq \top \mid \bot \mid lval \mid GV[iv][w] \mid id \mid IV \mid \diamond(exp^{+}) & & (expressions)
\end{array}
$$

Initial states and “ERROR” states of the program are define

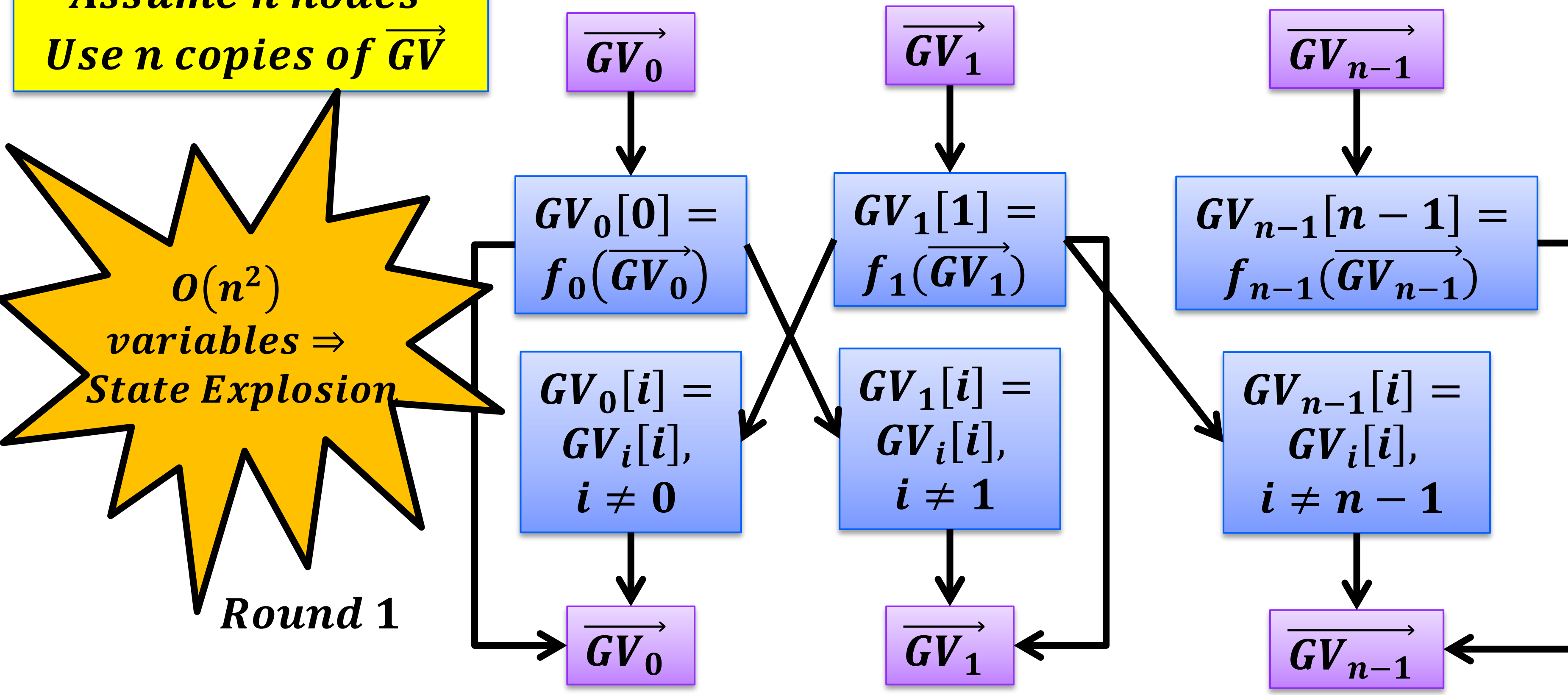
- State $\equiv$ value assigned to all variables

Verification $\equiv$ decide if there is an execution of the program that starts in an initial state and ends in an ERROR state

# Semantic Sequentialization: SEQSEM

**Node 0** $= f_0()$ **Shared Variables:** $\overrightarrow{GV} = GV[0], GV[1]$ **Node 1** $= f_1()$

*Assume n nodes*
*Use n copies of* $\overrightarrow{GV}$

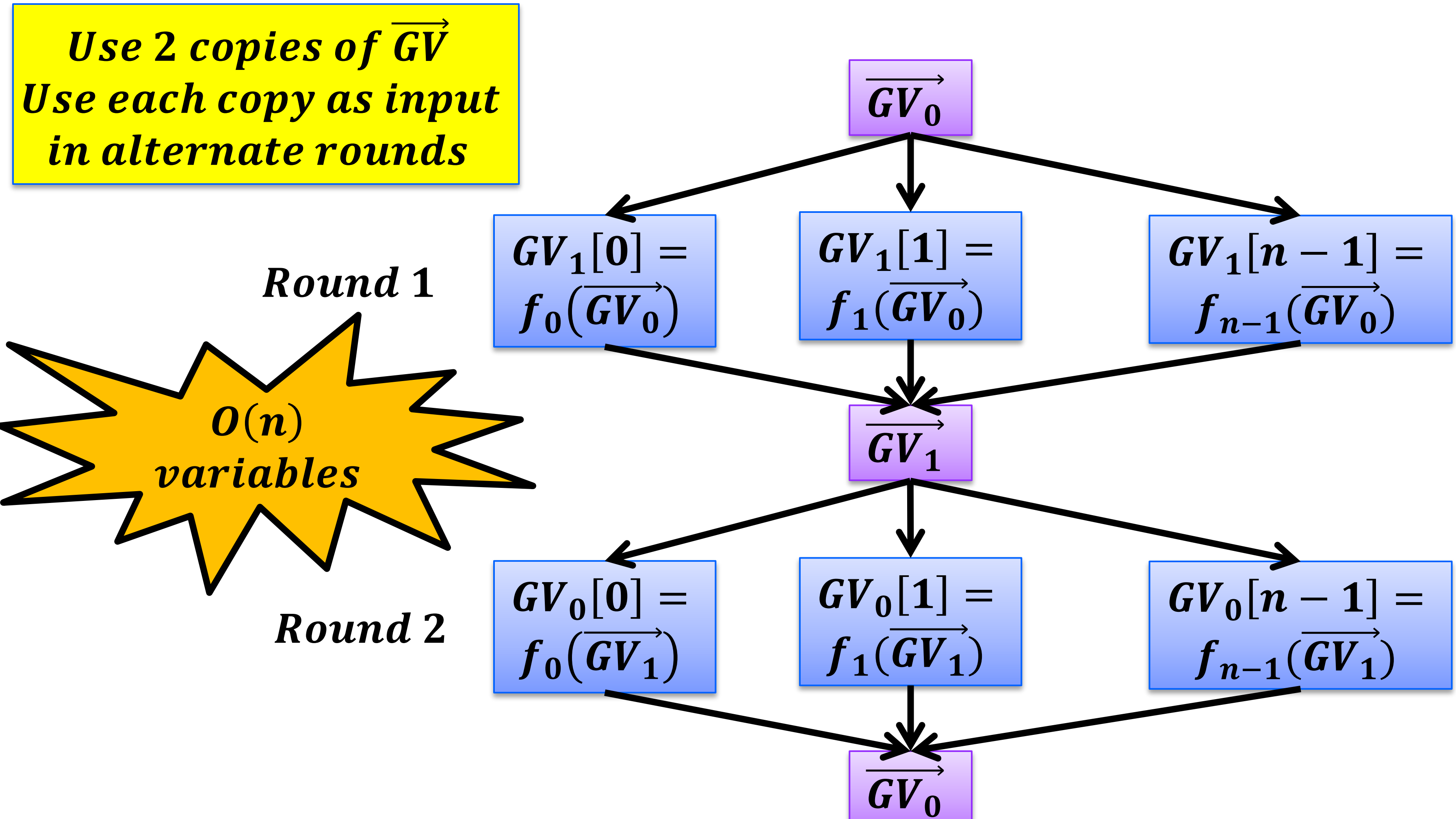



*Operations have independentce* $\Rightarrow$ *reordered sequentially.*

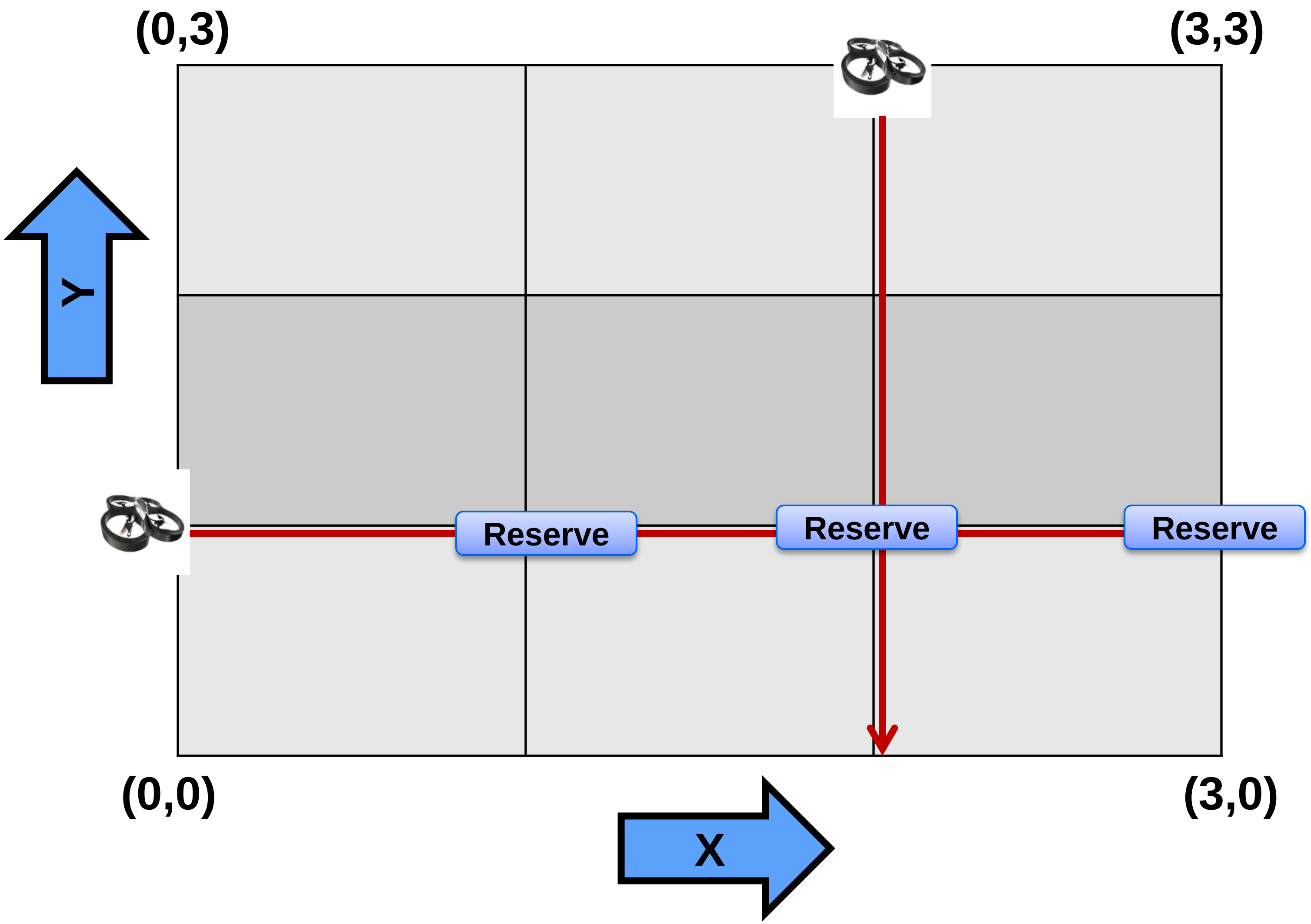
*Rounds are repeated in a loop.*

# Double Buffering Sequentialization: SEQDBL

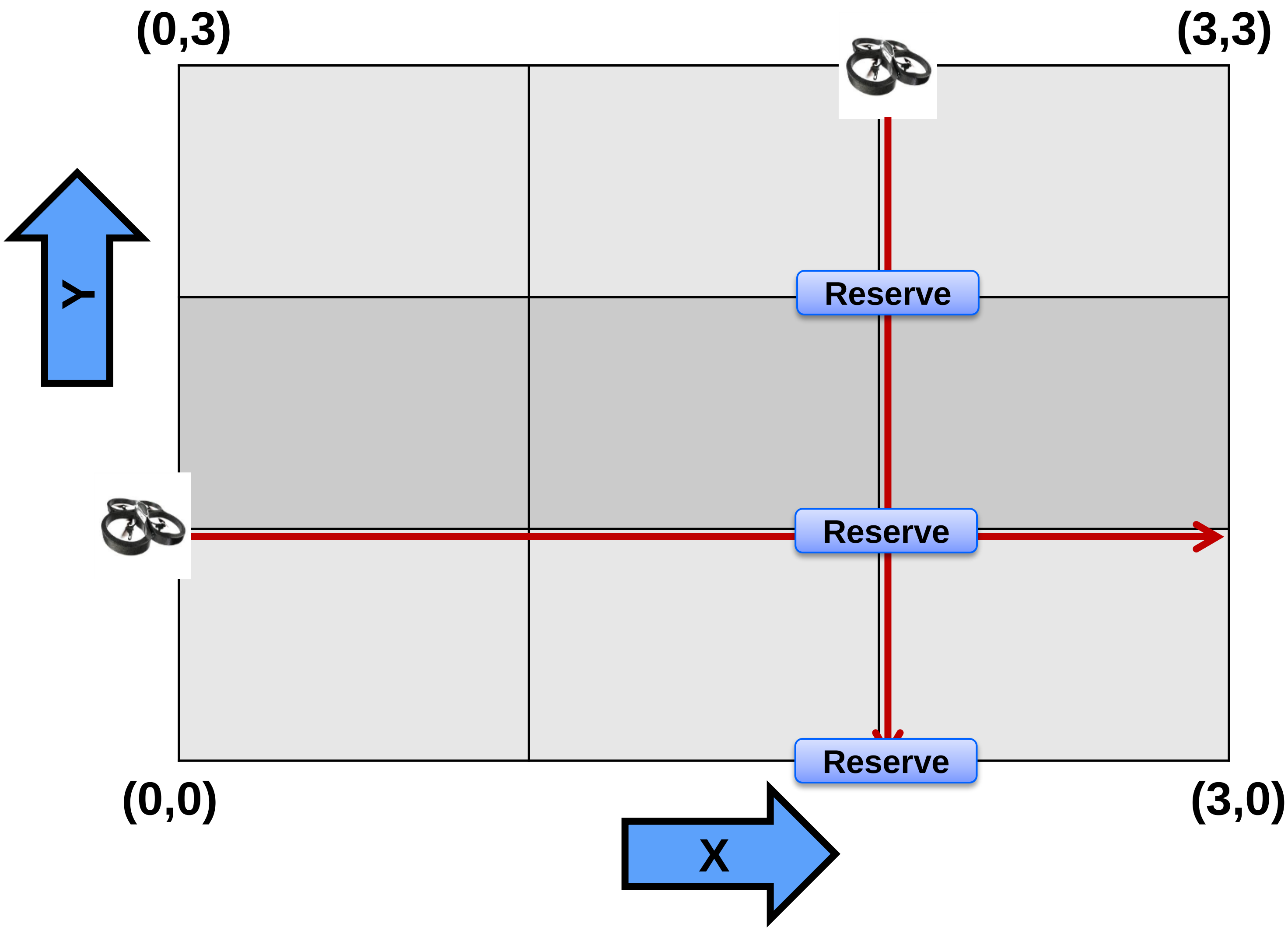
Node 0 $= f_0()$ Shared Variables: $\overrightarrow{GV} = GV[0], GV[1]$ Node 1 $= f_1()$



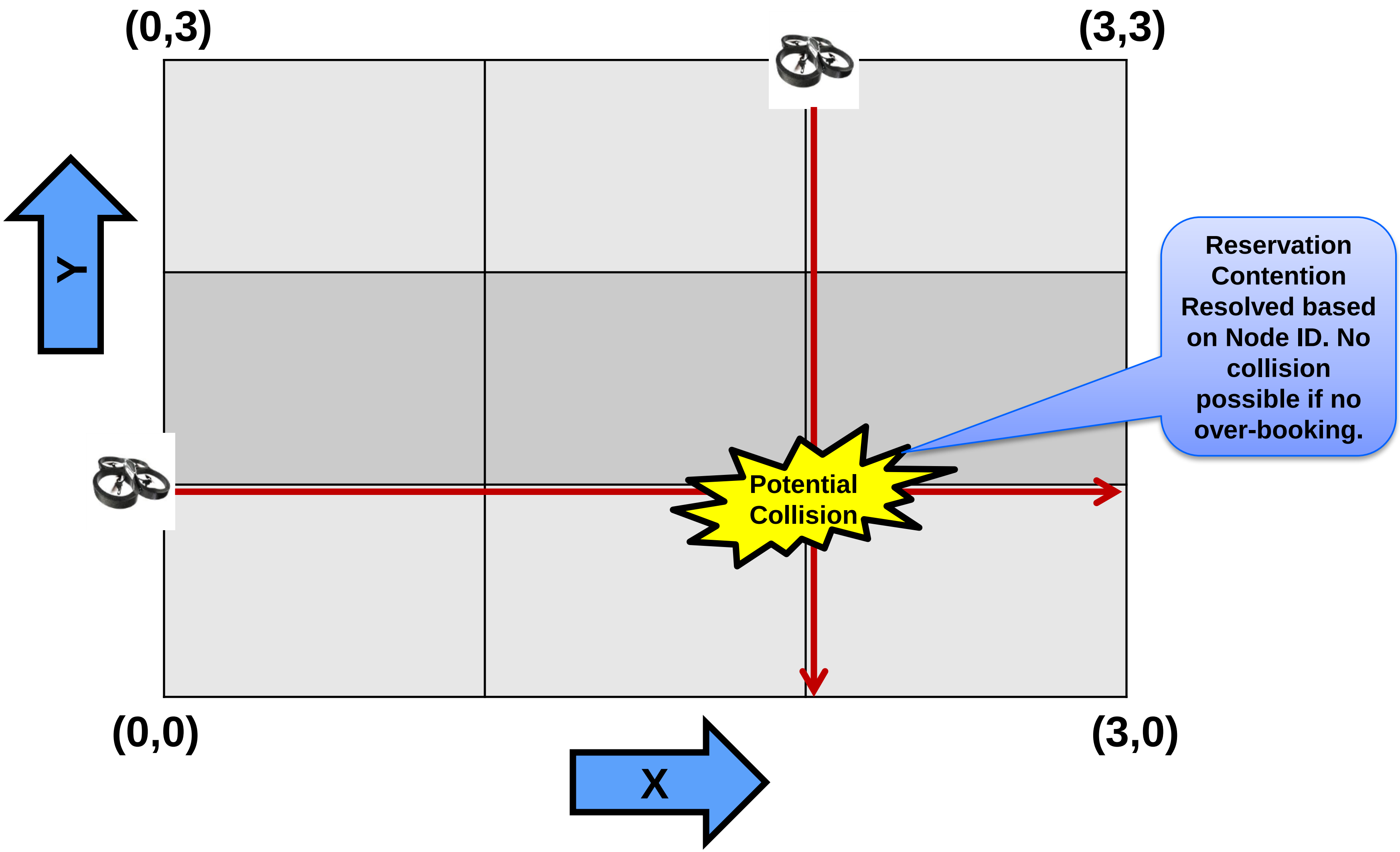
# Example: 2D Synchronous Collision Avoidance



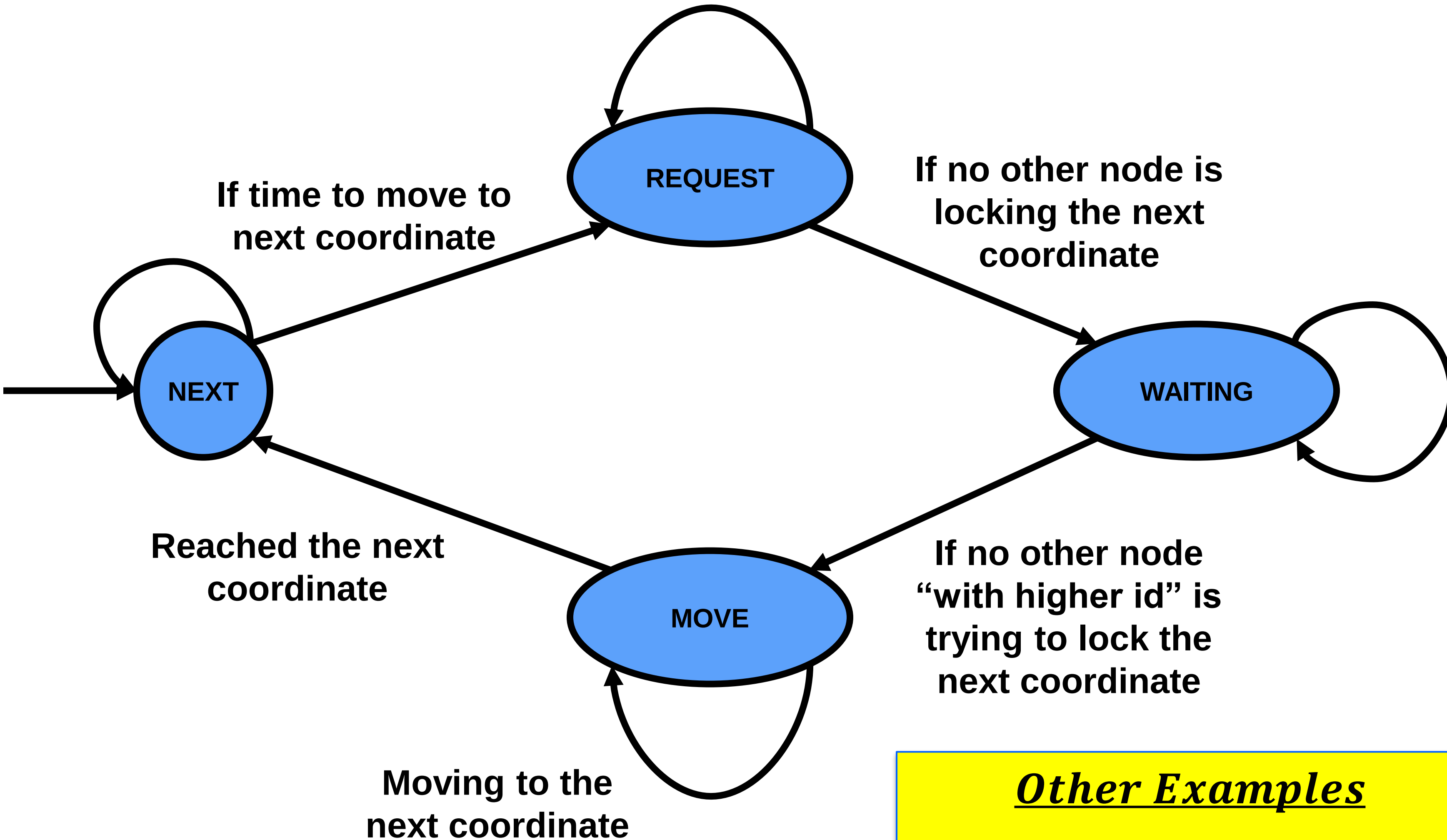
# Example: 2D Synchronous Collision Avoidance



# Example: 2D Synchronous Collision Avoidance



# 2D Collision Avoidance Protocol




***Other Examples***

**3D Collision Avoidance**

**Mutual Exclusion**

# Results: 3D Collision Avoidance

| 3DCOLL-OK-4x4 | | | | | | |
|---|---|---|---|---|---|---|
| $R$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| | $n=2$ | | $n=4$ | | $n=6$ | |
| 10 | 13 | 10 | 59 | 40 | 219 | 96 |
| 20 | 37 | 31 | 351 | 123 | 1014 | 480 |
| 30 | 48 | 48 | 406 | 202 | – | – |
| | $\mu$=2.213 $\sigma$=0.715 | | | | | |

| 3DCOLL-OK-7x7 | | | | | |
|---|---|---|---|---|---|
| $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| $n=2$ | | $n=4$ | | $n=6$ | |
| 31 | 35 | 323 | 148 | 1099 | 323 |
| 73 | 72 | 1262 | 401 | – | – |
| 142 | 113 | – | – | – | – |
| $\mu$=2.294 $\sigma$=0.763 | | | | | |

| 3DCOLL-BUG-4x4 | | | | | |
|---|---|---|---|---|---|
| $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| $n=2$ | | $n=4$ | | $n=6$ | |
| 8 | 9 | 49 | 36 | 123 | 96 |
| 24 | 36 | 119 | 101 | 410 | 210 |
| 42 | 44 | 206 | 155 | – | – |
| $\mu$=1.615 $\sigma$=0.425 | | | | | |

| 3DCOLL-BUG-7x7 | | | | | |
|---|---|---|---|---|---|
| $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| $n=2$ | | $n=4$ | | $n=6$ | |
| 22 | 23 | 194 | 114 | – | – |
| 57 | 76 | – | – | – | – |
| 117 | 134 | – | – | – | – |
| $\mu$=1.514 $\sigma$=0.344 | | | | | |

**SEQDBL is better**

$T_S, T_D = model\ checking\ time\ with\ SEQSEM, SEQDBL$

$$\mu, \sigma = Avg, StDev\ of\ \frac{T_S}{T_D}$$

$n = \#of\ nodes \quad R = \#of\ rounds \quad G \times G = grid\ size$

# Results: 2D Collision Avoidance

| 2DCOLL-OK-4x4 | | | | | | |
|---|---|---|---|---|---|---|
| $R$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| | $n=2$ | | $n=4$ | | $n=6$ | |
| 10 | 17 | 25 | 87 | 262 | 280 | 831 |
| 20 | 123 | 271 | 1474 | 2754 | – | – |
| 30 | 863 | 1301 | – | – | – | – |
| | $\mu$=0.446 $\sigma$=0.118 | | | | | |

| 2DCOLL-BUG1-4x4 | | | | | |
|---|---|---|---|---|---|
| $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| $n=2$ | | $n=4$ | | $n=6$ | |
| 3 | 2 | 12 | 11 | 30 | 22 |
| 8 | 7 | 36 | 29 | 80 | 75 |
| 12 | 15 | 57 | 51 | 144 | 105 |
| $\mu$=1.282 $\sigma$=0.264 | | | | | |

| 2DCOLL-BUG2-4x4 | | | | | |
|---|---|---|---|---|---|
| $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| $n=2$ | | $n=4$ | | $n=6$ | |
| 4 | 3 | 13 | 11 | 30 | 29 |
| 8 | 9 | 33 | 33 | 76 | 66 |
| 16 | 21 | 57 | 77 | 150 | 120 |
| $\mu$=1.056 $\sigma$=0.266 | | | | | |

| 2DCOLL-OK-7x7 | | | | | | |
|---|---|---|---|---|---|---|
| $R$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| | $n=2$ | | $n=4$ | | $n=6$ | |
| 10 | 74 | 146 | 395 | 1016 | 1707 | – |
| 20 | 1726 | 3096 | – | – | – | – |
| 30 | – | – | – | – | – | – |
| | $\mu$=0.598 $\sigma$=0.202 | | | | | |

| 2DCOLL-BUG1-7x7 | | | | | |
|---|---|---|---|---|---|
| $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| $n=2$ | | $n=4$ | | $n=6$ | |
| 7 | 7 | 32 | 24 | 101 | 70 |
| 15 | 22 | 94 | 55 | 345 | 150 |
| 40 | 35 | 180 | 91 | – | 223 |
| $\mu$=1.382 $\sigma$=0.517 | | | | | |

| 2DCOLL-BUG2-7x7 | | | | | |
|---|---|---|---|---|---|
| $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| $n=2$ | | $n=4$ | | $n=6$ | |
| 5 | 10 | 26 | 36 | 188 | 113 |
| 19 | 22 | 71 | 113 | 207 | 166 |
| 46 | 68 | 124 | 295 | 416 | 235 |
| $\mu$=0.906 $\sigma$=0.393 | | | | | |

Depends on the example

$T_S, T_D = \textit{model checking time with SEQSEM, SEQDBL}$

$\mu, \sigma = \textit{Avg, StDev of } \frac{T_S}{T_D}$

$n = \textit{\#of nodes} \quad R = \textit{\#of rounds} \quad G \times G = \textit{grid size}$

# Results: Mutual Exclusion

| MUTEX-OK | | | | | | |
|---|---|---|---|---|---|---|
| $R$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| | $n=6$ | | $n=8$ | | $n=10$ | |
| 60 | 406 | 396 | 1116 | 1051 | 2388 | 2268 |
| 80 | 850 | 806 | 2268 | 1967 | 4525 | 4249 |
| 100 | 1404 | 1381 | 3584 | 3452 | 7092 | 6764 |
| | $\mu$=1.040 $\sigma$=0.038 | | | | | |

| MUTEX-BUG1 | | | | | |
|---|---|---|---|---|---|
| $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| $n=6$ | | $n=8$ | | $n=10$ | |
| 184 | 175 | 517 | 439 | 1068 | 959 |
| 402 | 372 | 1013 | 925 | 2203 | 1812 |
| 734 | 686 | 1726 | 1566 | 3513 | 3287 |
| $\mu$=1.056 $\sigma$=0.060 | | | | | |

SEQSEM and SEQDBL similar

| MUTEX-BUG2 | | | | | |
|---|---|---|---|---|---|
| $T_S$ | $T_D$ | $T_S$ | $T_D$ | $T_S$ | $T_D$ |
| $n=6$ | | $n=8$ | | $n=10$ | |
| 233 | 216 | 637 | 553 | 1292 | 1167 |
| 500 | 462 | 1218 | 1112 | 2602 | 2139 |
| 890 | 838 | 2056 | 1860 | 4216 | 3742 |
| $\mu$=1.065 $\sigma$=0.056 | | | | | |

$T_S, T_D = \text{model checking time with } SEQSEM, SEQDBL$

$\mu, \sigma = Avg, StDev \text{ of } \frac{T_S}{T_D}$

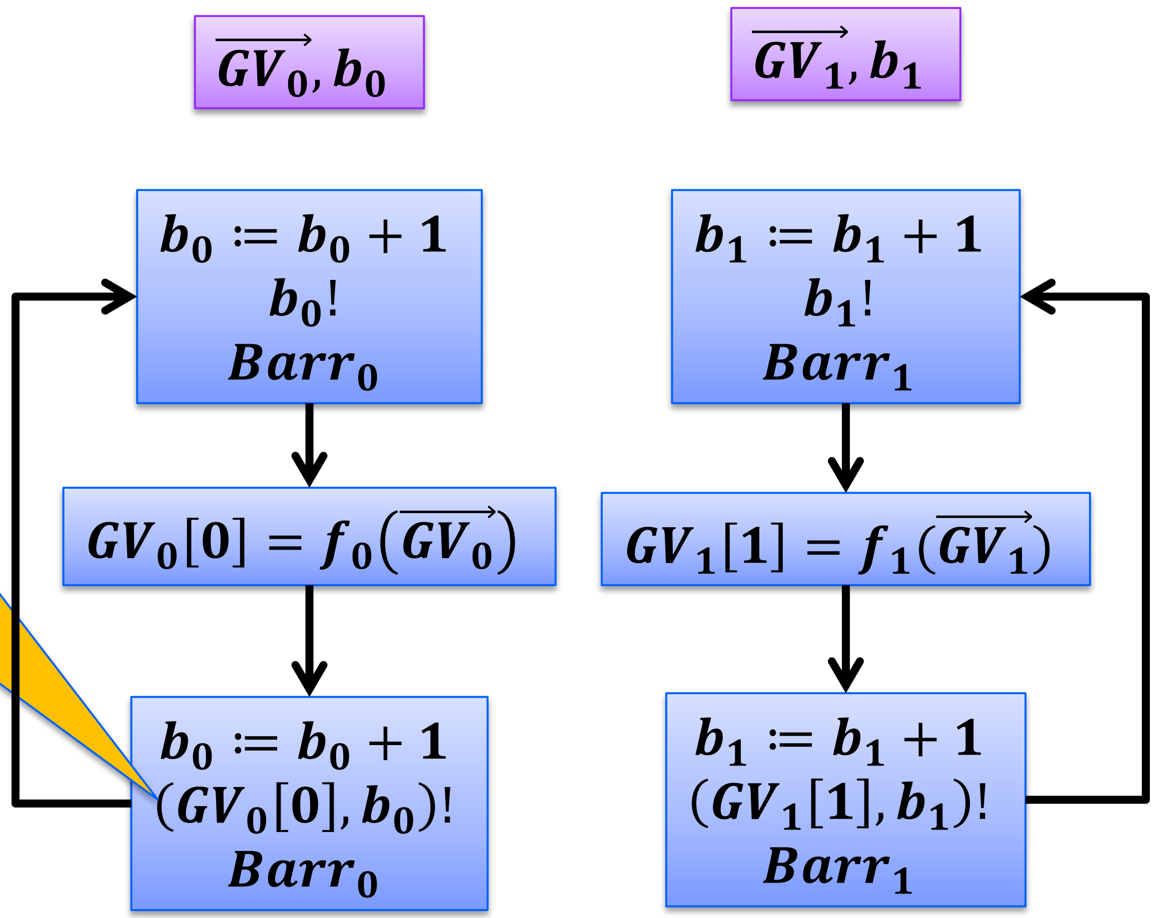
$n = \#\text{of nodes}$ $R = \#\text{of rounds}$ $G \times G = \text{grid size}$

# Synchronizer Protocol: 2BSYNC

**Node 0** $= f_0()$ **Shared Variables:** $\overrightarrow{GV} = GV[0], GV[1]$ **Node 1** $= f_1()$

***Use barrier variables***: $b_0, b_1$ ***Initialized to 0***

Atomic Send. Either both $GV_0[0]$ and $b_0$ are received, or none is received. Can be implemented on existing network stack, e.g, TPC/IP




$Barr_0 \equiv while(b_1 < b_0)\ \ skip;$

***Proof of correctness in paper***

# Tool Overview

Project webpage (http://mcda.googlecode.com)

- Tutorial (https://code.google.com/p/mcda/wiki/Tutorial)

Verification

- daslc --nodes 3 --seq --rounds 3 --seq-dbl --out tutorial-02.c tutorial-02.dasl
- cbmc tutorial-02.c (takes about 10s to verify)

Code generation & simulation

- daslc --nodes 3 --madara --vrep --out tutorial-02.cpp tutorial-02.dasl
- g++ …
- mcda-vrep.sh 3 outdir ./tutorial-02 …

DEMO

# Future Work

Improving scalability and verifying with unbounded number of rounds

Verifying for unbounded number of nodes (parameterized verification)

- Paper at SPIN'2014 Symposium

Asynchronous and partially synchronous network semantics

Scalable model checking

- Abstraction, compositionality, symmetry reduction, partial order reduction

Fault-tolerance, uncertainty, …

- Combine V&V of safety-critical and mission-critical properties

# Contact Information Slide Format

**Sagar Chaki**
Principal Researcher
SSD/CSC
Telephone: +1 412-268-1436
Email: chaki@sei.cmu.edu

**U.S. Mail**
Software Engineering Institute
Customer Relations
4500 Fifth Avenue
Pittsburgh, PA 15213-2612
USA

**Web**
www.sei.cmu.edu
www.sei.cmu.edu/contact.cfm

**Customer Relations**
Email: info@sei.cmu.edu
Telephone: +1 412-268-5800
SEI Phone: +1 412-268-5800
SEI Fax: +1 412-268-6257

# Synchronous Collision Avoidance Code

```
MOC_SYNC;

CONST X = 4; CONST Y = 4;
CONST NEXT = 0;
CONST REQUEST = 1;
CONST WAITING = 2;
CONST MOVE = 3;

EXTERN int
MOVE_TO (unsigned char x,
         unsigned char y);

NODE uav (id) { … }

void INIT () { … }

void SAFETY { … }
```

```
NODE uav (id)
{
  GLOBAL bool lock [X][Y][#N];
  LOCAL int state,x,y,xp,yp,xf,yf;
  void NEXT_XY () { … }
  void ROUND () {
    if(state == NEXT) { …
      state = REQUEST;
    } else if(state == REQUEST) { …
      state = WAITING;
    } else if(state == WAITING) { …
      state = MOVE;
    } else if(state == MOVE) { …
      state = NEXT;
    } } }
```

```
INIT
{
  FORALL_NODE(id)
    state.id = NEXT;
    //assign x.id and y.id non-deterministically
    //assume they are within the correct range
    //assign lock[x.id][y.id][id] appropriately

  //nodes don't collide initially
  FORALL_DISTINCT_NODE_PAIR (id1,id2)
    ASSUME(x.id1 != x.id2 || y.id1 != y.id2);
}

SAFETY {
  FORALL_DISTINCT_NODE_PAIR (id1,id2)
    ASSERT(x.id1 != x.id2 || y.id1 != y.id2);
}
```

# Synchronous Collision Avoidance Code

```
if(state == NEXT) {
  //compute next point on route
  if(x == xf && y == yf) return;
  NEXT_XY();
  state = REQUEST;
} else if(state == REQUEST) {
  //request the lock but only if it is free
  if(EXISTS_OTHER(idp,lock[xp][yp][idp] != 0)) return;
  lock[xp][yp][id] = 1;
  state = WAITING;
} else if(state == WAITING) {
  //grab the lock if we are the highest
  //id node to request or hold the lock
  if(EXISTS_HIGHER(idp, lock[xp][yp][idp] != 0)) return;
  state = MOVE;
}
```

```
else if(state == MOVE) {
  //now we have the lock on (xp,yp)
  if(MOVE_TO()) return;
  lock[x ][y][id] = 0;
  x = xp; y = yp;
  state = NEXT;
}
```