New Directions in Software Quality Assurance Automation

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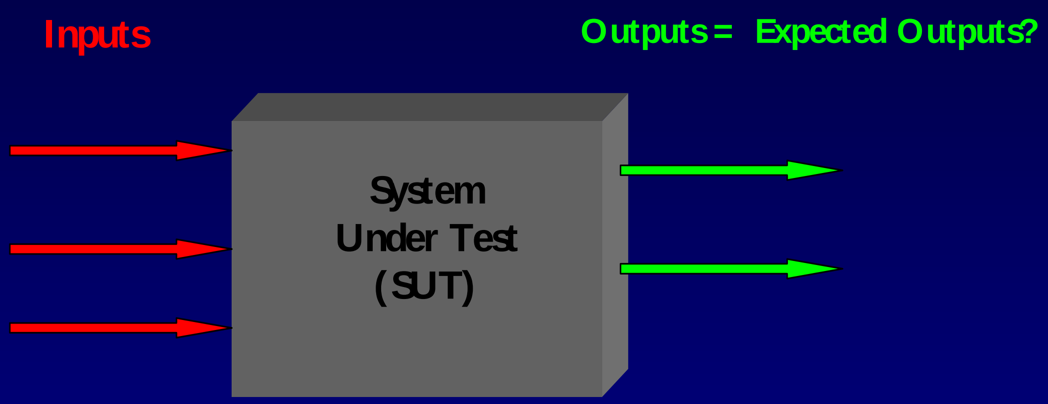
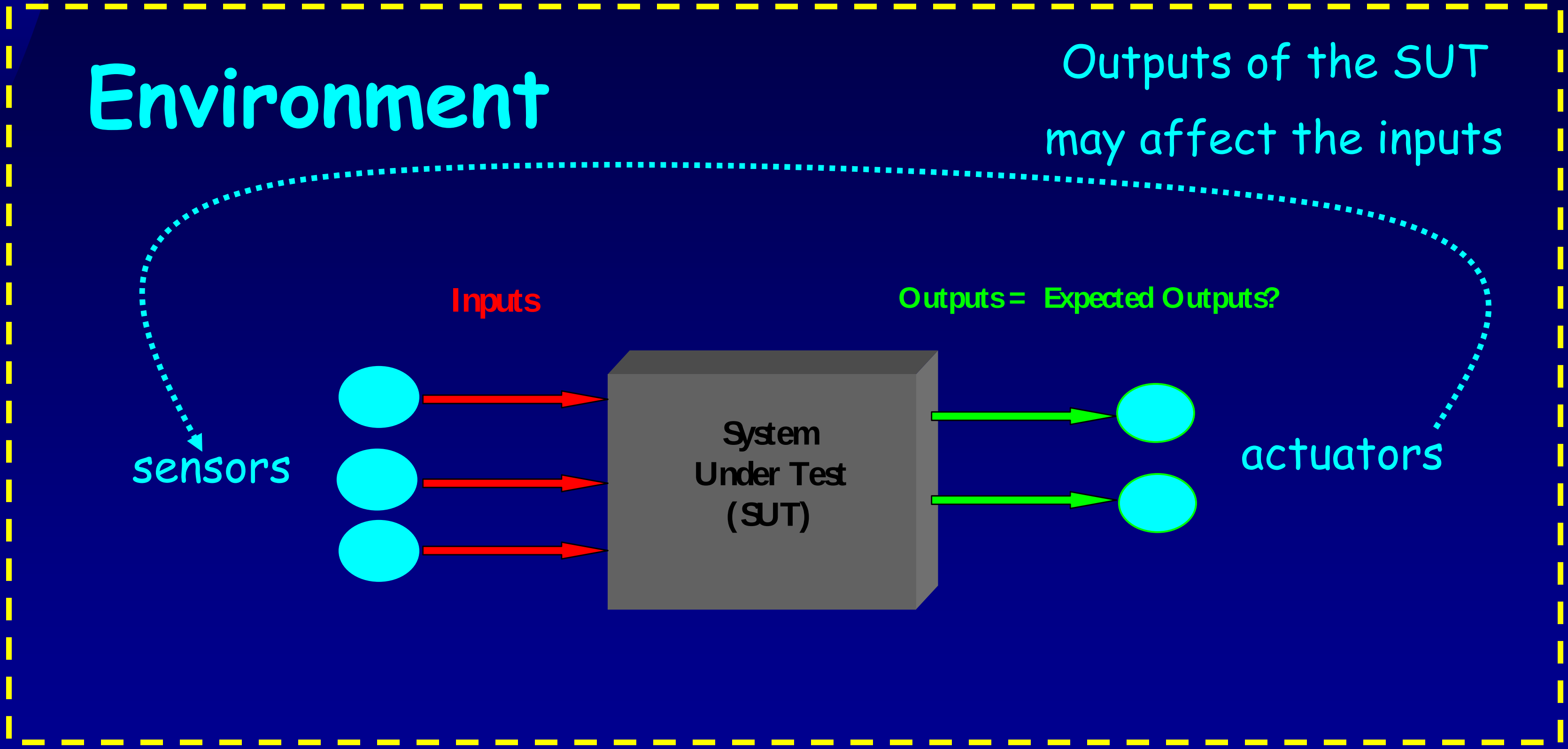
Black Box Testing



The main problems:

- ☞ How to create test cases
- ☞ How to run a test case
- ☞ How to verify the results of a test run

Black Box testing



The SUT may be a complex reactive real-time C3I system

Testing methodology

- We suggest (pseudo-)random test generation based on the environment models.

- It is best suited for a very special class of programs: reactive and real-time. These programs are of special interest for DoD-related applications.

The model of environment
(an approach to behavior modeling)

An **event** is any detectable action that is executed in the “black box” environment

- An event is a time interval
- An event has attributes: e.g., type, timing attributes, etc.
- There are two basic relations for events:

  precedence and **inclusion**
- The behavior of environment can be represented as a set of events (event trace)

The model of environment

Usually event traces have a certain structure (or constraints) in a given environment

Examples:

1. Shoot_a_gun is a sequence of a Fire event followed by either a Hit or a Miss event
2. Driving_a_car is an event that may be represented as a sequence of zero or more events of types

   go_straight, turn_left, turn_right, or stop

The model of environment

The structure of possible event traces for a given environment can be specified using event grammar

1. Shoot_a_gun::= Fire (Hit | Miss)

   Shooting::= Shoot_a_gun *

2. Driving_a_car::=

   go_straight

   (go_straight | turn_left | turn_right) *

   stop

   go_straight::= (accelerate | decelerate | cruise)

Sequential and parallel events

The precedence relation defines the partial order of events

Two events are not necessary ordered; i.e., they can happen concurrently

Examples

Shoot_a_gun::= Fire (Hit | Miss)

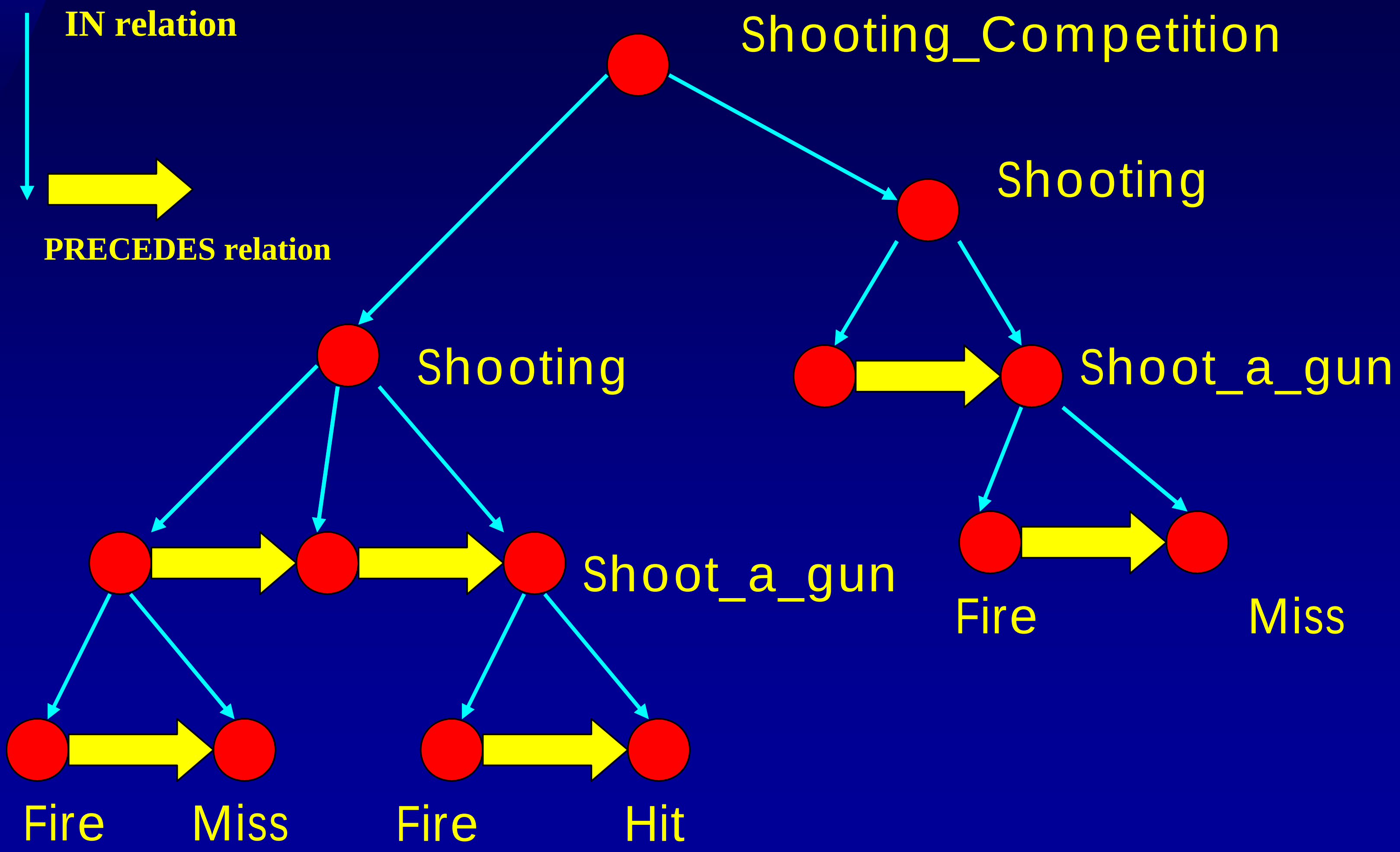
Shooting::= (* Shoot_a_gun *)

Shooting_Competition::= {* Shooting *}

This is a sequence

Those events may be parallel

Visual representation of event trace (not all events and relations are shown…)



Event attributes

```
Shoot_a_gun::=  Fire  (Hit  /Shoot_a_gun. points = Rand[1..10];
                ENCLOSING Shooting .points += Shoot_a_gun .points; / |
                          Miss /Shoot_a_gun. points = 0;/)

Shooting::=     / Shooting .points = 0; /
                (* Shoot_a_gun
                  /Shooting .ammo -=1;/ *) While (Shooting .ammo > 0)

Shooting_Competition ::= /num = 0;/
                {* /Shooting .id = num++;
                    Shooting .ammo =10;/
                  Shooting *} (Rand[2..100])
```

Production grammars

- Attribute event grammars (AEG) are intended to be used as a vehicle for automated random event trace generation
- It is assumed that the AEG is traversed top-down and left-to-right and only once to produce a particular event trace
- Randomized decisions about what alternative to take and how many times to perform the iteration should be made during the trace generation
- Attribute values are evaluated during this traversal

Using AEG to generate event traces and inputs to the SUT

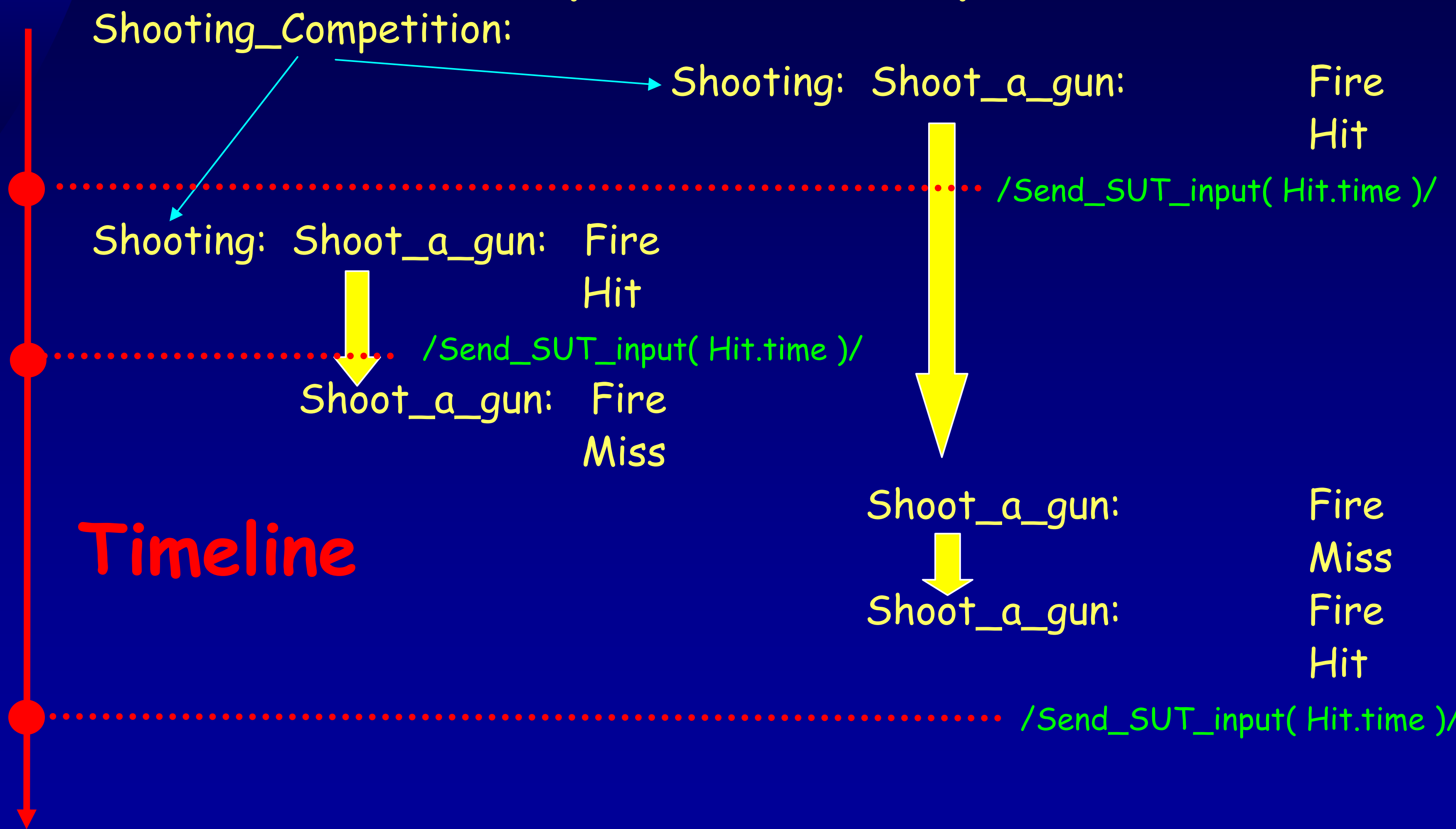
We can provide the probability of selecting an alternative

```
Shoot_a_gun::=  Fire
        ( P(0.3) Hit
        /Send_input_to_SUT( ENCLOSING Shooting .id, Hit .time);/ |
                -- this simulates SUT sensor input
         P(0.7) Miss )
```

We can generate a large number of event traces satisfying the constraints imposed by the event grammar

Production grammar

The grammar can be used in order to generate event traces and SUT inputs, for example:



Use cases

- ☞Event traces are essentially use cases
- ☞Examples of event traces can be useful for requirements engineering, prototyping, and system documentation

Example when SUT outputs are incorporated into the environment model

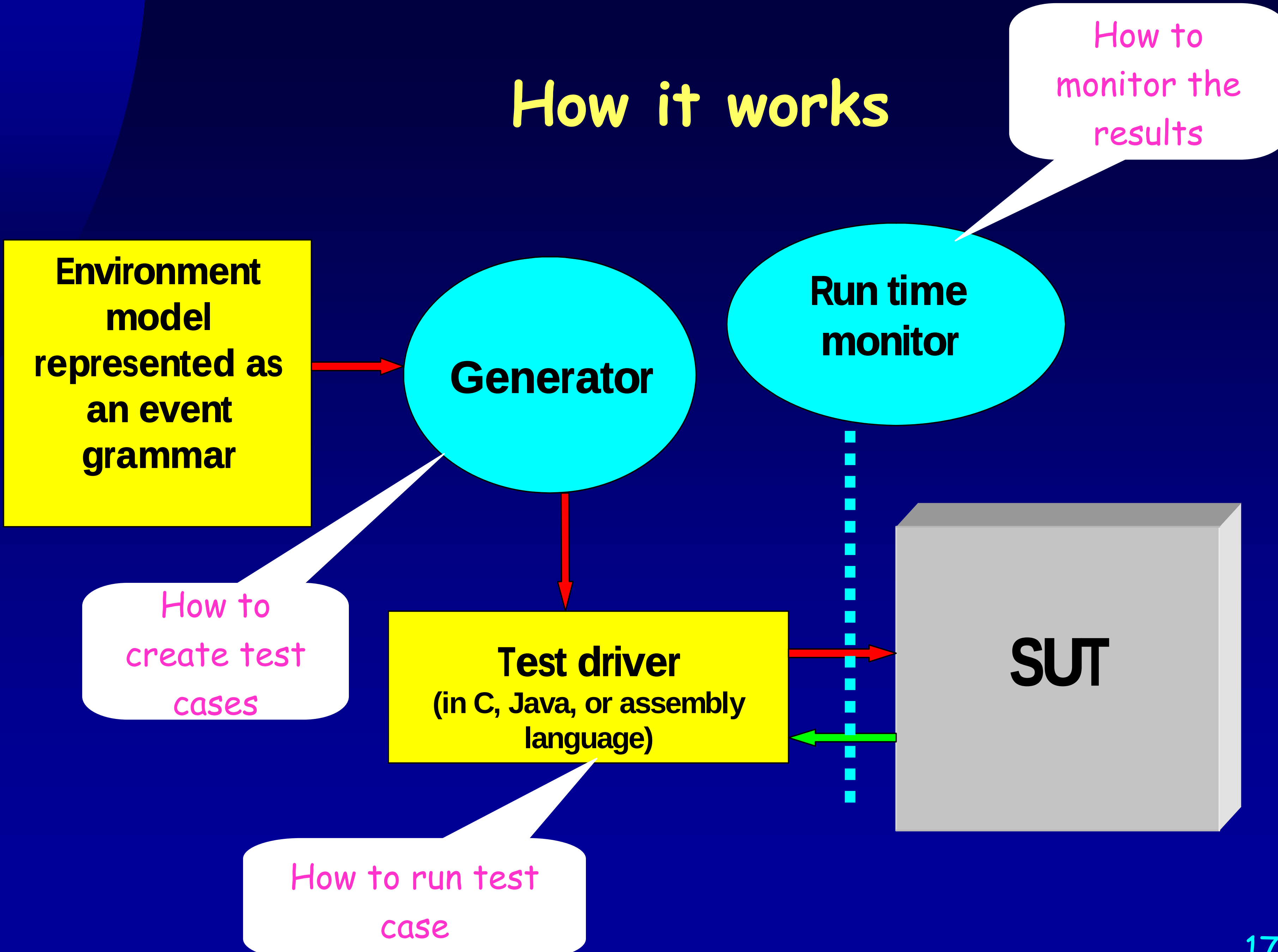
```
Attack::= {* Missile_launch  *} (Rand[1..5])
Missile_launch::= boost   middle_stage  WHEN(middle_stage.completed) Boom
middle_stage::= / middle_stage.completed = true;/
                (* CATCH    interception_launched (hit_coordinates)
                         -- this external event intercepts SUT output
                  WHEN (hit_coordinates == middle_stage .coordinates )
                  [  P(0.1)   hit_hard
                         / middle_stage.completed= false;
                          send_SUT_input(middle_stage .coordinates);
                                 -- this simulates SUT sensor input
                          Break; / -- breaks the iteration
                  ]
                 OTHERWISE  move
                *)
move ::= /adjust (ENCLOSING middle_stage .coordinates) ;
          send_SUT_input( ENCLOSING middle_stage .coordinates);
           -- this simulates SUT sensor input
          DELAY(50 msec); /
```

Prototype implementation

The test generator based on attributed event grammars has been implemented at NPS

It takes an AEG and generates a test driver in Java.

How it works



How to monitor the results
Environment model represented as an event grammar
Generator
Run time monitor
How to create test cases
Test driver
(in C, Java, or assembly language)
SUT
How to run test case

Software safety assessment

- In the previous example, the Boom event will occur in certain scenarios depending on the SUT outputs received by the test driver and random choices determined by the given probabilities

- If we run large enough number of (automatically generated) tests, the statistics gathered gives some approximation for the risk of getting to the hazardous state. This becomes a very constructive process of performing experiments with SUT behavior within the given environment model (“software-in-the-loop” simulations)

Qualitative Risk Analysis

```
Attack::= { Missile_launch } * (<=N)
Missile_launch::= boost   middle_stage  Boom
middle_stage::= ( CATCH  interception_launched(hit_coordinates)
                    -- this external event intercepts SUT output
                    [  P(p1) hit_hard
                      /send_hit_input(middle_stage.coordinates);
                       Break; / ]
                    OTHERWISE move
                  )*
```

- **Experimenting with increasing or decreasing N and p1 we can conclude what impact those parameters have on the probability of a hazardous outcome, and find thresholds for SUT behavior in terms of N and p1 values**

Qualitative Risk Analysis (2)

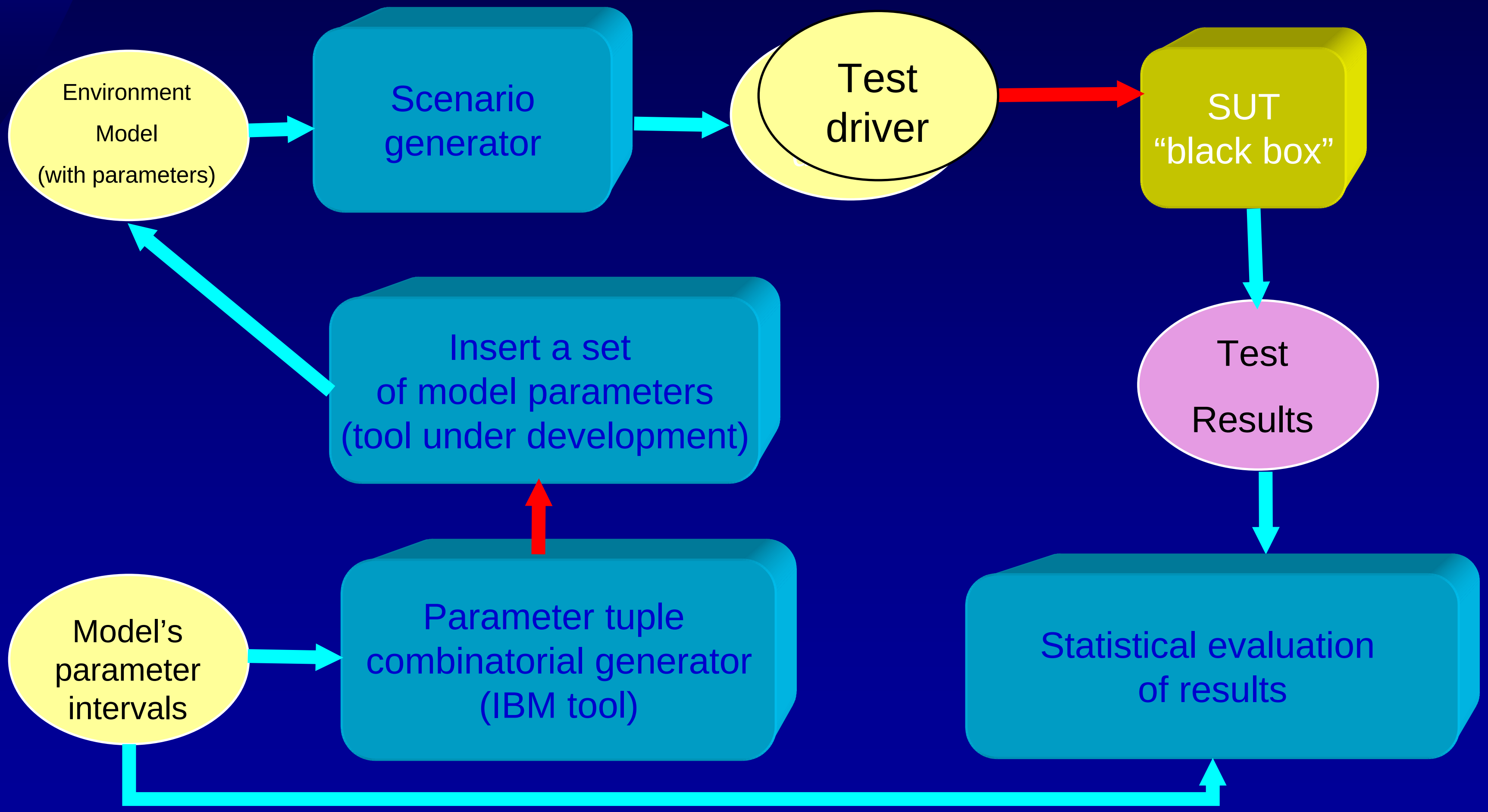
- We can change some parameters in the model and repeat the set of tests. If the frequency of reaching a hazardous state changes, we can find out how the parameter values influence the probability to reach a hazard state

- We suggest to use the **combinatorial testing technique** based on orthogonal arrays, an approach well familiar to statisticians

Qualitative Risk Analysis (3)

- The same conjecture that stipulates that the fault in behavior of the SUT in most cases depends either on a **single parameter value** or on an interaction of a **pair of parameter values** could be applied to the system safety testing. This conjecture still has to be verified by experiments
- Combinatorial approach will significantly **reduce the number** of experiments needed to establish statistically sound conclusions about probabilities to reach hazard state for different environment model settings
- In order to apply combinatorial testing techniques the values of model parameters have to be split into a **finite number of equivalence classes**, a technique well known in software component testing

SUT safety assessment with automated scenario generation



The main advantages

- ☞ The whole testing process can be automated
- ☞ The AEG formalism provides powerful high-level abstractions for environment modeling
- ☞ It is possible to run many more test cases with better chances to succeed in exposing an error
- ☞ It addresses the regression testing problem – generated test drivers can be saved and reused.
- ☞ AEG is well structured, hierarchical, and scalable
- ☞ The environment model itself is an asset and could be reused

Why it will fly

- Environment model specified by AEG provides for high-level domain-specific formalism for testing automation
- The generated test driver is efficient and could be used for real-time test cases
- Different environment models can be designed; e.g., for testing extreme scenarios by increasing probabilities of certain events, or for load testing
- Experiments running SUT with the environment model provide a constructive method for quantitative and even qualitative software safety assessment
- Environment models can be designed on early stages of system design, can provide environment simulation scenarios or use cases, and can be used for tuning the requirements and for prototyping efforts

Questions, please?

Backup slides

Example – simple calculator environment model

```
Use_calculator:   (* Perform_calculation *);
Perform_calculation:
        Enter_number  Enter_operator  Enter_number
        WHEN (Enter_operator.operation == '+')
        / Perform_calculation.result =
                Enter_number[1].value + Enter_number[2].value; /
        ELSE
        / Perform_calculation.result =
                Enter_number[1].value - Enter_number[2].value; /
        [ P(0.7) Show_result ];
```

Example – simple calculator environment model

```
Enter_number:           / Enter_number.value= 0; /
        (* Press_digit_button
          / Enter_number.digit = RAND[0..9];
            Enter_number.value =
               Enter_number.value * 10 + Enter_number.digit;
           enter_digit(Enter_number.digit); /  *) Rand[1..6];
Enter_operator:
               ( P(0.5) / enter_operation('+');
                          Enter_operator .operation= '+'; / |
                P(0.5) / enter_operation('-');
                          Enter_operator .operation= '-'; / ) ;

Show_result:   /show_result();/ ;
```

Example 2 –Infusion Pump model

```
CARA_environment:    { Patient, LSTAT, Pump };

Patient:          / Patient.bleeding_rate= BR; /
                  (*  / Patient.volume +=
                            ENCLOSING CARA_environment ->
                                   Pump.Flow – Patient.bleeding_rate;
                      Patient.blood_pressure =
                                   Patient.volume/50 – 10;
                      Patient.bleeding_rate += RAND[-9..9]; /
                    WHEN (Patient.blood_pressure > MINBP)
                            Normal_condition
                    ELSE
                            Critical_condition
                  *) [EVERY 1 sec] ;
```

Example 2 –Infusion Pump model

```
LSTAT:    Power_on / send_power_on(); /
          (* / send_arterial_blood_pressure(
                  ENCLOSING CARA_environment->
                          Patient.blood_pressure); /
          *) [EVERY 1 sec] ;

Pump:     Plugged_in
          /  send_plugged_in();
             Pump.rotation_rate = RR;
             Pump.voltage = V; /
          { Voltage_monitoring, Pumping };
```

Example 2 –Infusion Pump model

```
Voltage_monitoring:     (*  / ENCLOSING Pump.EMF_voltage =
                                  ENCLOSING Pump.rotation_rate * REMF;
                              send_pump_EMF_voltage(
                                  ENCLOSING Pump.EMF_voltage); /
                        *) [ EVERY 5 sec]  ;
Pumping:
                        (* / ENCLOSING Pump. rotation_rate =
                                  ENCLOSING  Pump. voltage * VRR;
                             ENCLOSING Pump. flow =
                                  ENCLOSING Pump. rotation_rate * RRF; /
                          CATCH set_pump_voltage( ENCLOSING Pump.voltage)
                          Voltage_changed
                          [ P(p1)  Occlusion
                                  / ENCLOSING Pump.occlusion_on =  True;
                                    send_occlusion_on(); / ]
                          WHEN ( ENCLOSING Pump.occlusion_on)
                          [ P(p2) / ENCLOSING Pump.occlusion_on  =False;
                                   send_occlusion_off(); / ]
                        *) [EVERY 1 sec] ;
```

Backup slides
Program monitoring and test oracles

(How to verify the results of a test run)

Objective: to develop unifying principles for program monitoring activities

Suggested solution: to define a precise model of program behavior as a set of events – event trace

Monitoring activities in software design can be implemented as computations over program execution traces.

Examples:

- Assertion checking (test oracles)
- Debugging queries
- Profiles
- Performance measurements
- Behavior visualization

Program Behavior Models

- Program monitoring activities can be specified in a uniform way using program **behavior models** based on the event notion
- An **event** corresponds to any detectable action; e.g., subroutine call, expression evaluation, message passing, etc. An event corresponds to a time interval
- Two partial order binary relations are defined for events: **precedence** and **inclusion**
- An event has **attributes**: type, duration, program state at beginning or end of the event, value,…

Program Behavior Models

- **Event grammar** specifies the constraints on configurations of events generated at the run time (in the form of axioms, or "lightweight semantics" of the target language)

- Some axioms are generic; e.g., transitivity and distributivity

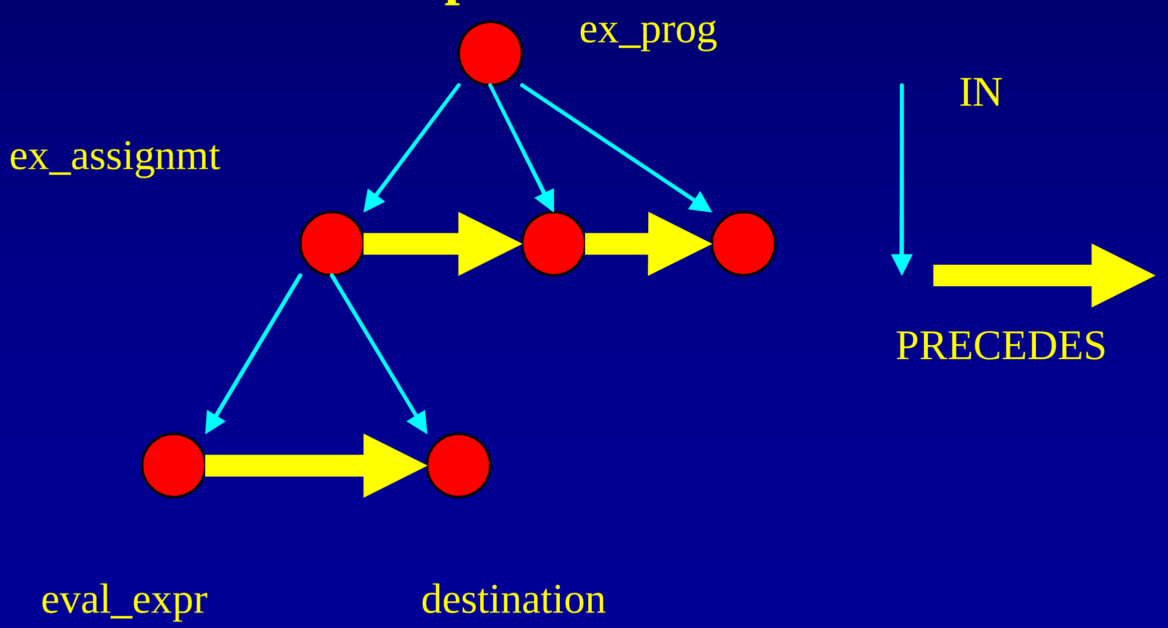
A PRECEDES B and B PRECEDES C → A PRECEDES C

A IN B and B PRECEDES C → A PRECEDES C

Example of an Event Grammar

```
ex_prog:: ex_stmt *
ex_stmt:: ex_assignmt | ex_read_stmt | …
ex_assignmt:: eval_expr  destination
```

Example of an event trace



Program Monitoring

- Monitoring activities: assertion checking, profiles, performance measurements, dynamic QoS metrics, visualization, debugging queries, intrusion detection
- Program monitoring can be specified in terms of computations over event traces
- We introduce a specific language FORMAN to describe computations over event traces (based on event patterns and aggregate operations over events)

FORMAN language

- Event patterns

```
x: func_call & x.name == "A"
eval_expr :: ( variable )
```

- List of events

```
[ exec_assignmt FROM ex_prog]
```

- List of values

```
[ x: exec_assignmt FROM ex_prog APPLY x.value]
```

FORMAN language

- Aggregate Operations

```
MAX/[ x: exec_assignmt FROM ex_prog APPLY x.value]
```

```
AND/[ x: exec_assignmt FROM ex_prog APPLY x.value > 17]
```

Or

```
FOREACH x: exec_assignmt FROM ex_prog x.value > 17
```

Examples

1) Profile

```
SAY( "Number of function A calls is "
   CARD[ x: func_call & x.name == "A"
                             FROM ex_prog ]
```

Event pattern

Aggregate operation

2) Generic debugging rule (typical error description)

```
FOREACH e: eval_expr :: (v: variable)
                                   FROM ex_prog
  EXISTS d: destination FROM e.PREV_PATH
            v.source_code = d.source_code
   ONFAIL SAY("Uninitialized variable "
          v.source_code "is used in expression " e)
```

Event attribute

Examples

3) Debugging query

```
SAY("The history of variable x "
[d: destination & d.source_code == "x" FROM ex_prog
  APPLY d.value ] )
```

4) Traditional debugging print statements

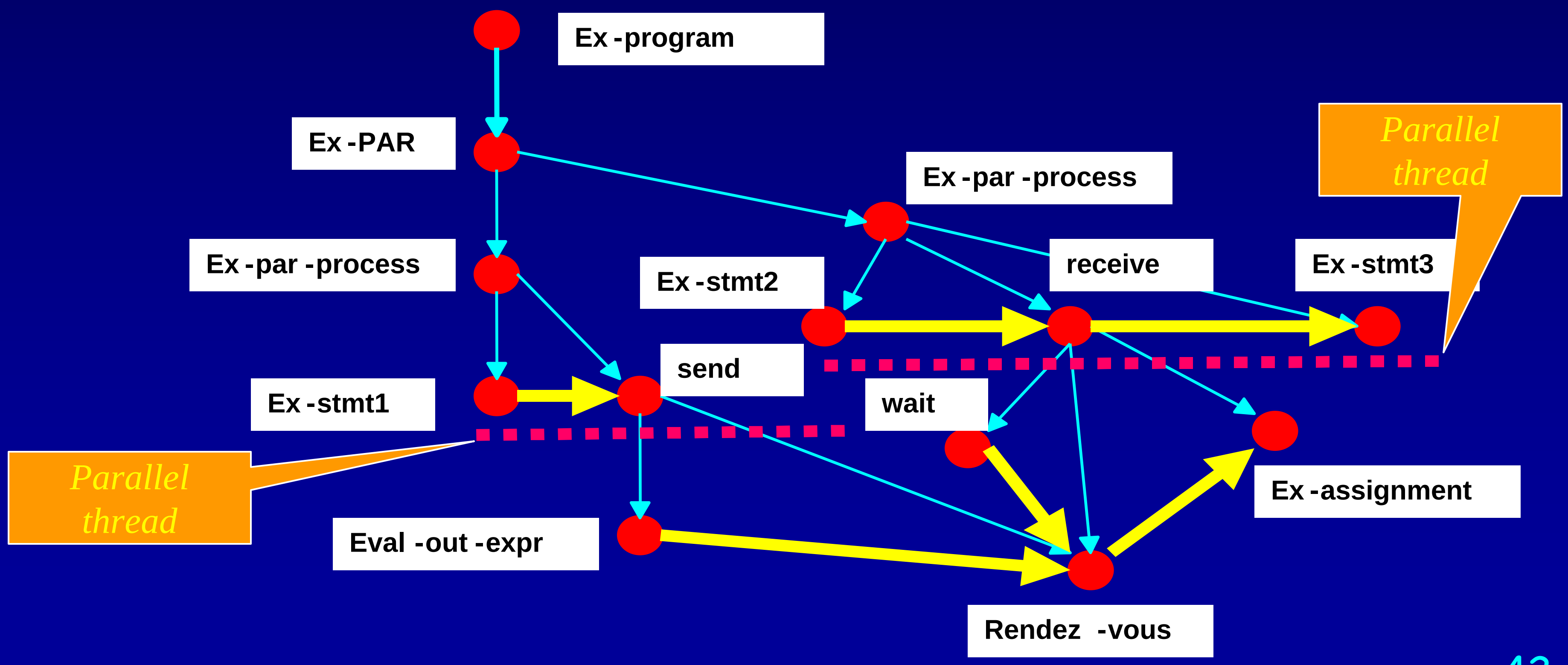
```
FOREACH f: func_call & f.name == "A"
                              FROM ex_prog
  f.value_at_begin(
           printf("variable x is %d\n", x) )
```

Event attribute

Expression
Evaluated at the run time

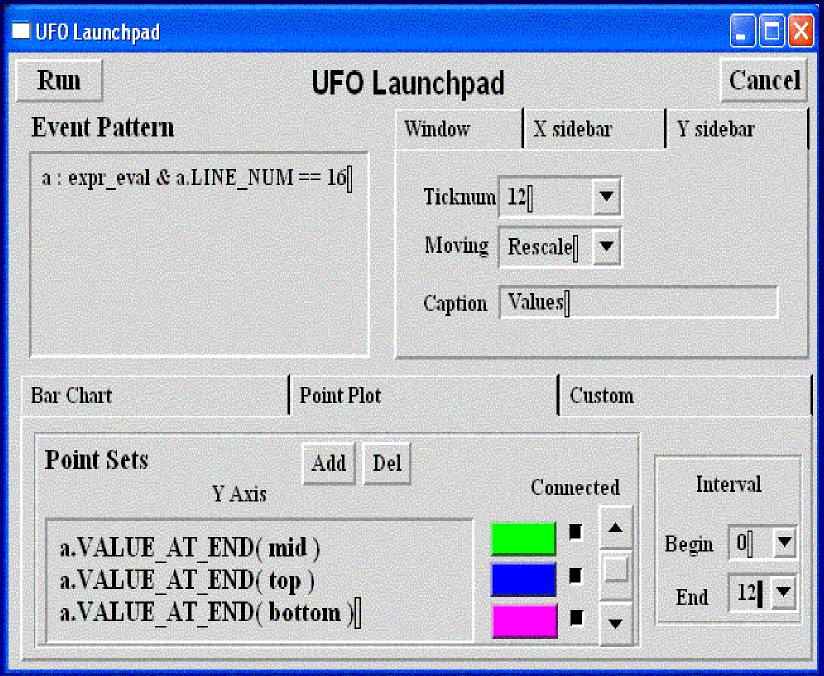
Example of event trace representing a synchronization event (send/receive a message)

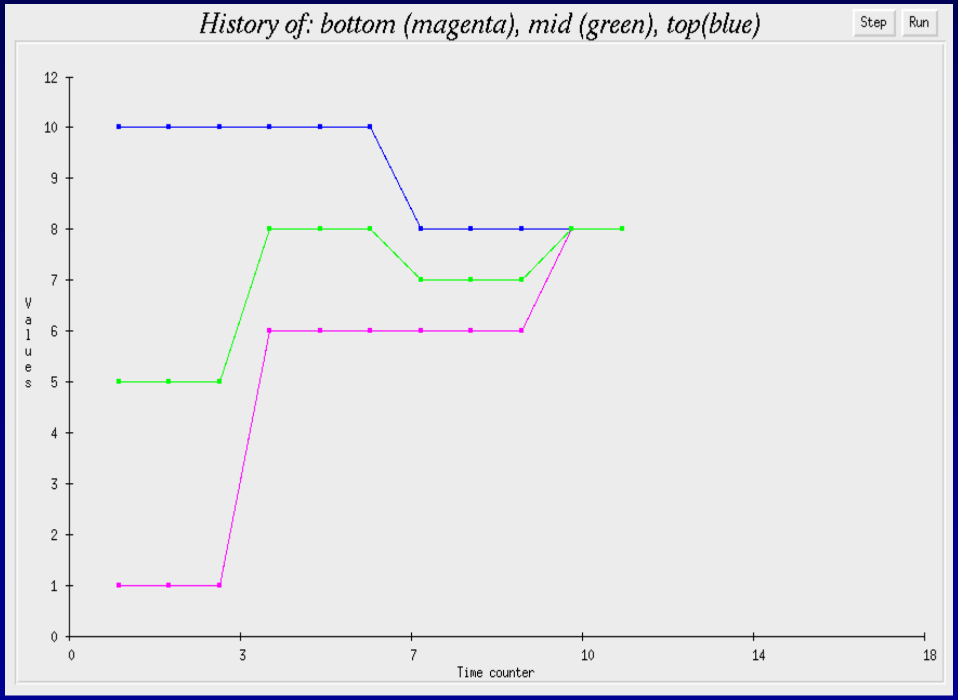
```
par     --launches two parallel processes
        seq     -- first parallel thread
                stmt1
                channel1 ! Out-expr    -- sends a message
                …
        seq     -- another parallel thread
                stmt2
                channel1 ? Var         -- receives a message
                …
```



Program visualization (UFO project)

Visualization prototype for Unicon/ALAMO (Jointly with C.Jeffery, NMSU)





Point plot example for a binary search program

The novelty claims of our approach

- **Uniform framework** for program monitoring based on precise behavior models and event trace computations
- Computations on the event traces can be implemented in a **nondestructive** way via automatic instrumentation of the source code or even of the executables (Dyninst approach)
- Can specify **generic trace computations**: typical bug detection, dynamic QoS metrics, profiles, visualization, …
- Both **functional** and **non-functional** requirements can be monitored
- Yet another approach to the **aspect-oriented** paradigm

Accomplished projects and work in progress

- Assertion checker for a Pascal subset (via interpreter)
- Assertion checker for the C language (via source code instrumentation)
- Assertion checker and visualization tool for the Unicon language (via Virtual Machine monitors)
- Dynamic QoS metrics, UniFrame project (via glue and wrapper instrumentation), funded by ONR
- Intrusion detection and countermeasures (via Linux kernel library instrumentation using NAI GSWTK), funded by the Department of Justice Homeland Security Program
- Automated test driver generator for reactive real time systems based on AEG environment models, funded by Missile Defense Agency

Some publications

- M. Auguston, Program Behavior Model Based on Event Grammar and its Application for Debugging Automation, 2nd Int'l Workshop on Automated and Algorithmic Debugging, AADEBUG'95, Saint-Malo, May 1995, pp. 277-291.

- M. Auguston, A. Gates, M. Lujan, Defining a Program Behavior Model for Dynamic Analyzers, 9th International Conference on Software Engineering and Knowledge Engineering, SEKE'97, Madrid, June 1997, pp. 257-262.

- M.Auguston, Assertion Checker for the C Programming Language based on computations over event traces, in Proceedings of the Fourth International Workshop on Algorithmic and Automatic Debugging, AADEBUG'2000, Munich, August 28-30, 2000, pp.90-99 on-line proceedings at http://www.irisa.fr/lande/ducasse/aadebug2000/proceedings.html

- M. Auguston, C. Jeffery and S. Underwood. A Framework for Automatic Debugging. Proceedings of the IEEE 17th International Conference on Automated Software Engineering, ASE'02, Edinburgh, September 2002, IEEE Computer Society Press, pp.217-222.

- Mikhail Auguston, James Bret Michael, Man-Tak Shing, Environment Behavior Models for Scenario Generation and Testing Automation, in Proceedings of the First International Workshop on Advances in Model-Based Software Testing (A-MOST'05), the 27th International Conference on Software Engineering ICSE'05, May 15-16, 2005, St. Louis, USA, http://a-most.argreenhouse.com, also in the ACM Digital Library

Summary of the event grammar approach

- Behavior models based on event grammars provide a uniform framework for software testing and debugging automation
- Can be implemented in a nondestructive way via automatic instrumentation
- Automated tools can be built to support all phases of the testing process
- Provides a good potential for reuse: environment models, generic debugging rules, test drivers for regression testing
- Provides high-level abstractions for testing and debugging tasks, hence is easy to learn and use
- Well suited for reactive real-time system testing

Why bother?

- Testing and debugging consume more than 50% of total software development cost.
- If the proposed research is transferred into practice and reduces costs by 1% of the 50% of the $400 billion software industry, the potential economic impact would be around $2 billion per year.