Algebraic Patterns of Vulnerabilities in Binary Code

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The Defense Advanced Research Projects Agency (DARPA) launched the Cyber Grand Challenge to create defensive systems with purposes of automated, scalable, machine-speed detection of vulnerabilities and cyber infections.

MAYHEM
ForAllSecure team
from Pittsburg

XANDRA
TECH team
From Ithaka
New York

Mechanical Phish
Shellphish team
from Santa Barbara,
California,

ALL THESE TEAMS USE SYMBOLIC (ALGEBRAIC APPROACH) IN DETECTION OF VULNERABILITIES IN BINARY CODE

Problems:

1. Pattern Matching.
   Redundant. Too many False Positive.
2. Simulation in isolated environment.
   Insufficient. Deep-hidden vulnerabilities cannot be detected.
3. Analysis of high-level programming languages.
   Insufficient. Security issues are on the level of third-party (non-compiled) libraries.

Our approach:

Use the algebraic matching and symbolic execution of binary code model.

1. Create algebraic model of binary code.
2. Formalize the existed vulnerabilities as algebraic patterns.
3. Provide algebraic matching of given vulnerability models with binary code model and detect the vulnerability candidates.
4. Prove the reachability of the detected vulnerability by symbolic execution.

Algebra of Behaviors

Algebra of behaviors was developed by D. Gilbert and A. Letichevsky (Senior) in 1997
It consider the operations over **actions** and **behaviors**.

Prefixing operation *a.B* means that action *a* follows behaviour *B*. The operation of *nondeterministic choice* of behaviours *u* + *v* establishes alternative behaviours. The algebra has three terminal constants: successful termination Δ, deadlock 0, and unknown behaviour $\perp$. The parallel and sequential composition are defined on the behaviors.

Example:

B0 = a1.a2.B1 + a3.B2,
B1 = a4.Δ,
B2 =…

The example define the order of event. The behavior B0 has two alternative - first is two actions a1 and a2 and then the rest behavior B1 or action a3 and rest behavior B2. Behavior B1 is action a4 and end of behavior etc.

Algebra of Behaviors

Every action is also defined by a couple, namely, the **precondition** and **postcondition** of an action, given as an expression in some formal theory.

Action(A,B) = (A > B) && !(A == 0) -> B = (B + 1)/A

The semantic of the action presented in C-like syntax means that if precondition *(A > B) && !(A == 0)* is true for concrete values of *A* and *B* or is satisfiable for symbolic (arbitrary) values of *A* and *B*, then we can change attribute B by the assignment *B = (B + 1)/A*. The action can be parametrized by the attributes used in the action's conditions.

Translation of x86 Assembler to Algebra of Behaviors

Listing after disassembling:

```
8049865:   2d e0 01 1d 08        sub eax,0x81d01e0
804986a:   c1 f8 02              sar eax,0x2
804986d:   89 c2                 mov edx,eax
8049876:   75 01                 jne 8049879
```

Model of binary code behavior:

```
B8049865 = sub(1,eax,0x81d01e0).B804986a,
B804986a = sar(1,eax,0x2).B804986d,
B804986d = mov(1,edx,eax,mov).B8049876,
B8049876 = jmp(1,jne).B8049879
```

Translation of x86 Assembler to Algebra of Behaviors

ALGEBRAIC ENVIRONMENT:

- the set of general- and special-purpose registers. Some attributes are identified as names of registers: *ax,al,bx,bl,..,eax,ebx,…,rax,rbx,…,ebp,esp,rbp,rsp,rip*
- physical memory that can be considered as the function *Memory(addr)*, where *addr* is the available memory address

Bx1 = cjne.Bz + !cjne.Bx2
Bx2 = …
cjne(n,A,B) = !(A == B) -> PI = PI + z + 3;FLAG_C = (B > A)
!cjne(n,A,B) = (A == B) -> PI = PI + 3;

Translation of x86 Assembler to Algebra of Behaviors

Set of Instructions is converted to

```
0000000000425060 <SSL_CTX_use_certificate_file>:
  425060:   41 55                   push   r13
  425062:   41 54                   push   r12
  425064:   49 89 f5                mov    r13,rsi
  425067:   55                      push   rbp
  425068:   53                      push   rbx
  425069:   49 89 fc                mov    r12,rdi
  42506c:   89 d5                   mov    ebp,edx
  42506e:   48 83 ec 08             sub    rsp,0x8
  425072:   e8 d9 24 fe ff          call   407550 <BIO_s_file@plt>
  425077:   48 89 c7                mov    rdi,rax
  42507a:   e8 a1 31 fe ff          call   408220 <BIO_new@plt>
  42507f:   48 85 c0                test   rax,rax
  425082:   0f 84 b0 00 00 00       je     425138
<SSL_CTX_use_certificate_file+0xd8>
  425088:   4c 89 e9                mov    rcx,r13
```

Set of Algebra Behavior Expressions

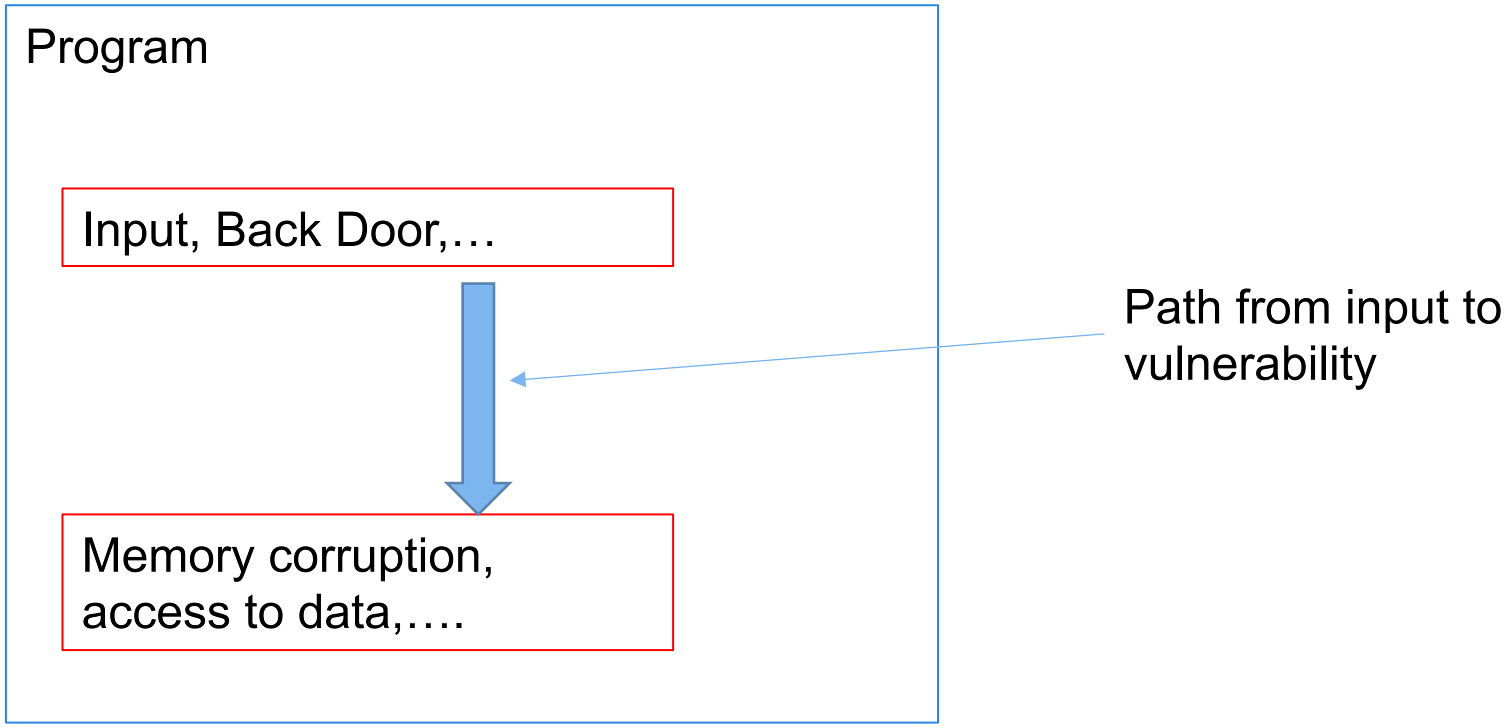
```
B425060 = a_push_33766.B425062,
B425062 = a_push_33767.B425064,
B425064 = a_mov_33768.B425067,
B425067 = a_push_33769.B425068,
B425068 = a_push_33770.B425069,
B425069 = a_mov_33771.B42506c,
B42506c = a_mov_33772.B42506e,
B42506e = a_sub_33773.B425072,
B425072 = a_call_33774.call B407550.B425077,
B425077 = a_mov_33775.B42507a,
B42507a = a_call_33776.call B408220.B42507f,
B42507f = a_test_33777.B425082,
B425082 = a_je_33778.B425138 + a_alt_je_33779.B425088,
B425088 = a_mov_33780.B42508b,
```

Set of Algebra Behavior Actions

```
a_push_33766 = Operator(1  -> ("x86: action 'push 425060';")
(rip := 4345954)),
a_push_33767 = Operator(1  -> ("x86: action 'push 425062';")
(rip := 4345956)),
a_mov_33768 = Operator(1  -> ("x86: action 'mov 425064';")
(rip := 4345959; r13 := rsi)),
a_push_33769 = Operator(1  -> ("x86: action 'push 425067';")
(rip := 4345960)),
a_push_33770 = Operator(1  -> ("x86: action 'push 425068';")
(rip := 4345961)),
a_mov_33771 = Operator(1  -> ("x86: action 'mov 425069';")
(rip := 4345964; r12 := rdi)),
a_mov_33772 = Operator(1  -> ("x86: action 'mov 42506c';")
(rip := 4345966; ebp := edx)),
a_sub_33773 = Operator(1  -> ("x86: action 'sub 42506e';")
(rip := 4345970; rsp := rsp - 8; ZF := (rsp - 8 = 0); PF :=
((rsp - 8) = 0); SF := (rsp - 8) < 0))),
a_call_33774 = Operator(1  -> ("x86: action 'call 425072';")
(rip := 4345975)),
a_mov_33775 = Operator(1  -> ("x86: action 'mov 425077';")
(rip := 4345978; rdi := rax)),
a_call_33776 = Operator(1  -> ("x86: action 'call 42507a';")
(rip := 4345983)),
a_test_33777 = Operator(1  -> ("x86: action 'test 42507f';")
(rip := 4345986)),
a_je_33778 = Operator((ZF = 1)  -> ("x86: action 'je
425082';")(rip := 4345992)),
a_alt_je_33779 = Operator(( ~(ZF = 1))  -> ("x86: action 'je
425082';")(rip := 4345992)),
a_mov_33780 = Operator(1  -> ("x86: action 'mov 425088';")
(rip := 4345995; rcx := r13)),
```

Algebraic Patterns of Vulnerabilities

$$\mathit{VulnerabilityPattern} = \mathit{IntruderInput};\ \mathit{ProgramBehavior};\ \mathit{VulnerabilityPoint}$$



Algebraic Patterns of Vulnerabilities

Input of string → Stack Allocation → Rewriting of return code

BUFFER OVERFLOW VULNERABILITY

vulnerabilityBufferOverflow = input; X1; allocateStack; X2; writeStack,

input = mov(9, eax, 0x66). mov(10, ebx, 0x11). lea(11, ecx, MemoryOperand). call(12, MemoryOperand),

allocateStack = push(1,ebp).mov(2,ebp,esp).sub(3,esp,N),

writeStack = movs(8, MemoryOperand, MemoryOperand) + mov(5, MemoryOperand, regGen)

Algebraic Patterns of Vulnerabilities

ACTIONS:

call(12,MemoryOperand) = Forall(i:int, 0<=i<LengthSocket) -> Input(ecx + i) = true,
mov(2,ebp,esp)=1->StackAddr=ebp,

movs(8,MemoryOperand,MemoryOperand) = Input(RefMemorySrc) &&(StackAddr==RefMemoryDest) -> 1,
mov(5, MemoryOperand, regGen) = Input(RefMemorySrc) && (StackAddr == RefMemoryDest) -> 1,

mov(x, GenReg, MemoryOperand) = Input(RefMemorySrc) -> Input(GenReg),
mov(x, MemoryOperand, MemoryOperand) = Input(RefMemorySrc) -> Input(RefMemoryDest)

Sufficient conditions of vulnerability:

1. The bytes are written in address that is equal to the top stack pointer;
2. The bytes shall be received from the registers after system call

Behavior Matching

The first level of matching is to find behavior expressions that will find the behavior corresponding to the algebraic pattern of a vulnerability.

Behavior matching anticipates solving behavior expressions.

The task of solving behavior equations is formulated as follows. Let *B0* be the system of behavior equations:
B0 = R(a1, a2, … , B1, B2, …,),
B1 = R(a11, a12, …, B11, B12, …), …
where *B1, B2, … B11, B12, ...* are the behaviors and *a1, a2, …* are actions. The behavior *B0* shows translated binary code.

Let behavior *X* be an unknown behavior containing a vulnerability. The task is to find *X*, that is *B0 = Y; X; Z* and *X = vulnerabilityBufferOverflow*

Model Matching

Model matching is performed by the symbolic modelling of a given behavior that was obtained by behavior matching.

During symbolic modelling, we apply the actions for which we detect the satisfiability of the expression *Env && Prec*, where *Env* is a symbolic environment of the model of the binary code and *Prec* is the precondition of the matched action.

If it is satisfiable, then we perform the postcondition operations in the pattern environment and in the environment of the binary code model.

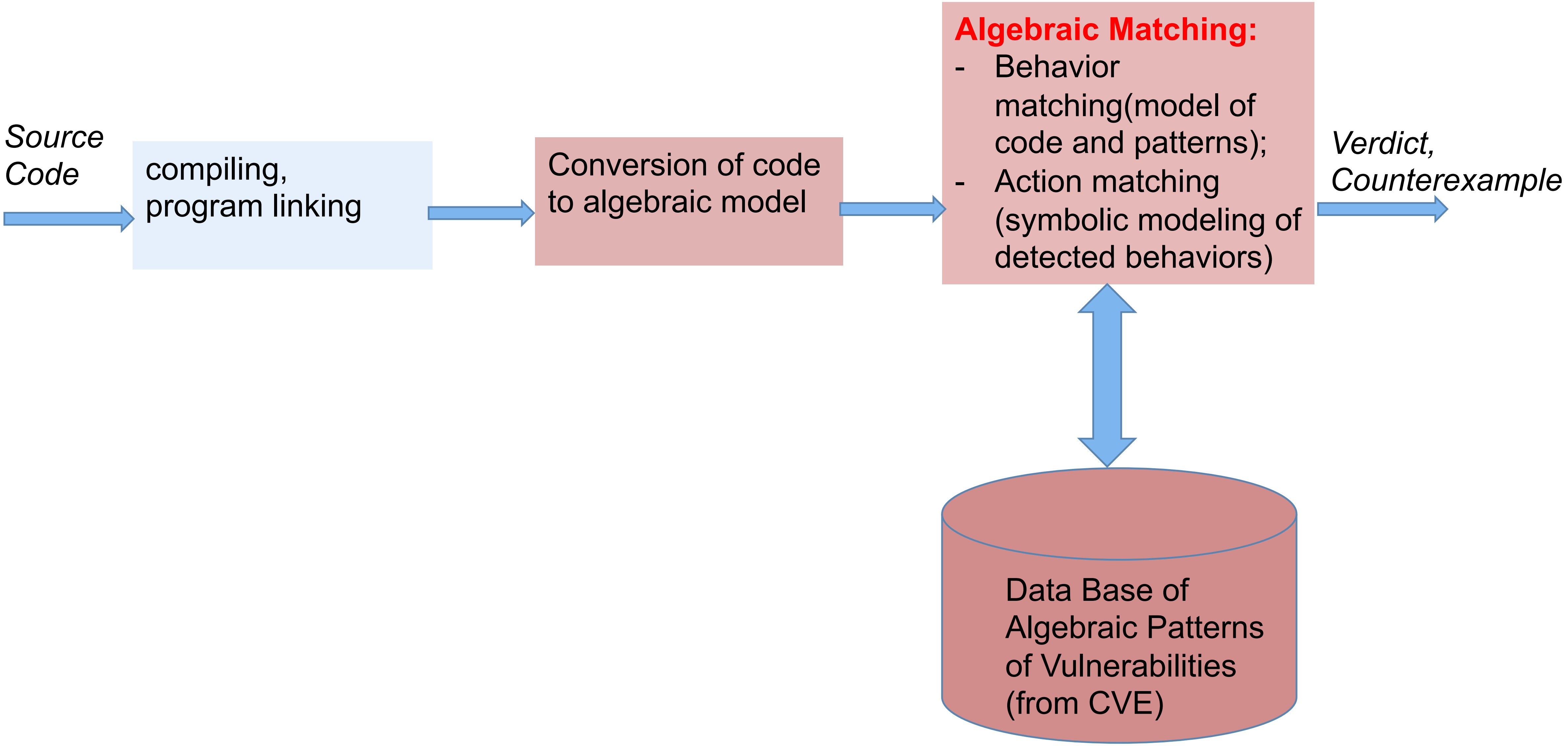
If we reach the vulnerability point in the pattern, then we have a scenario that leads from the input point.

Exploit Generation

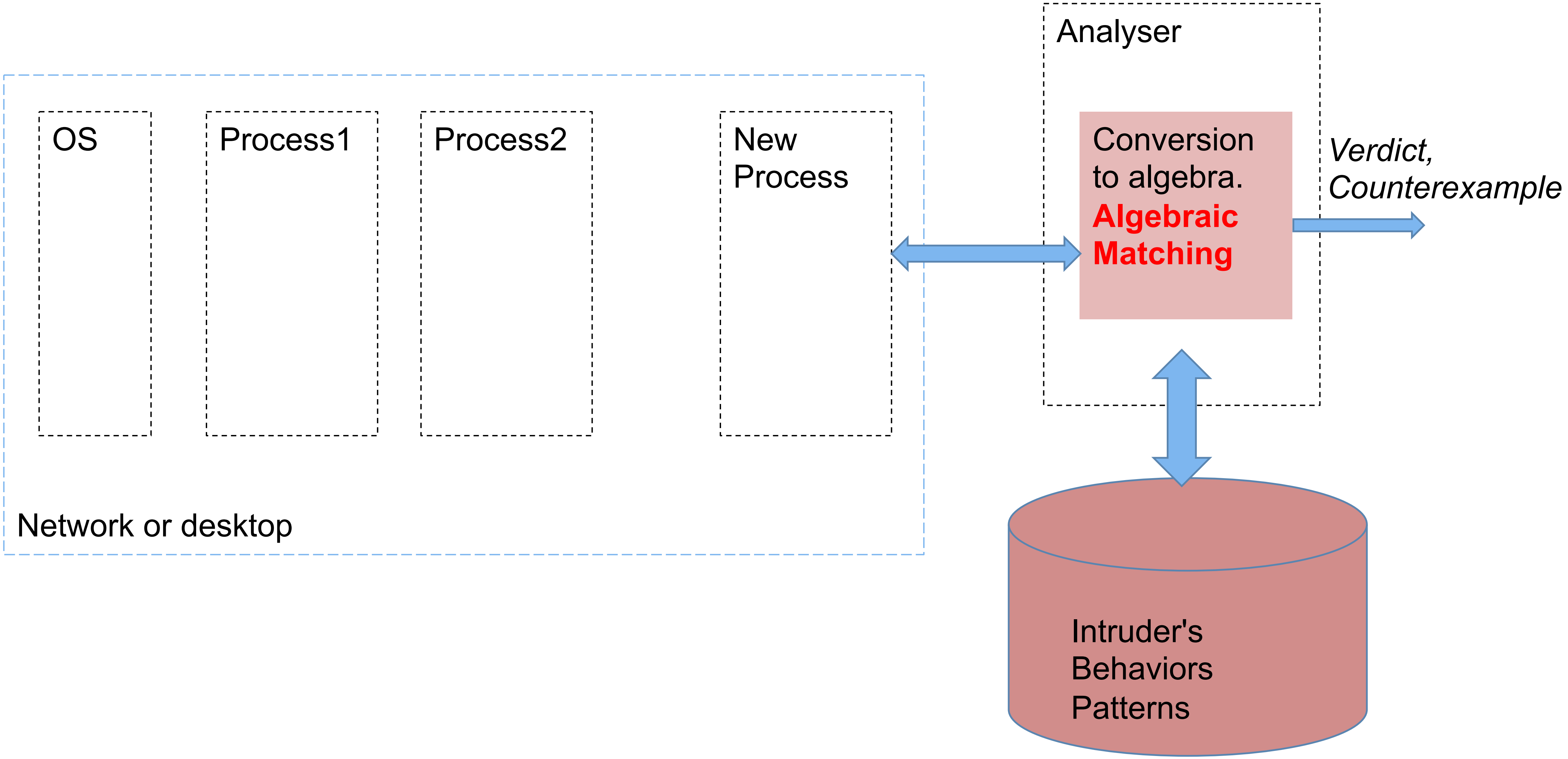
With the symbolic environment represented by the set of formulae, it is possible to realize a concrete scenario or to define input values that cause stack buffer overflow.

Backward symbolic modeling to the input point gives the initial formula that covers the values enabling exploits to perform malicious actions.

Detection of Vulnerabilities in Binary Code



Analysis of Suspicious Process



Platform for Detection of Vulnerabilities in Binary Code

- Upload the binary code;
- Disassembling;
- Conversion to behavior algebra;
- Matching for vulnerabilities;
- OPEN for creation the new patterns of vulnerabilities.

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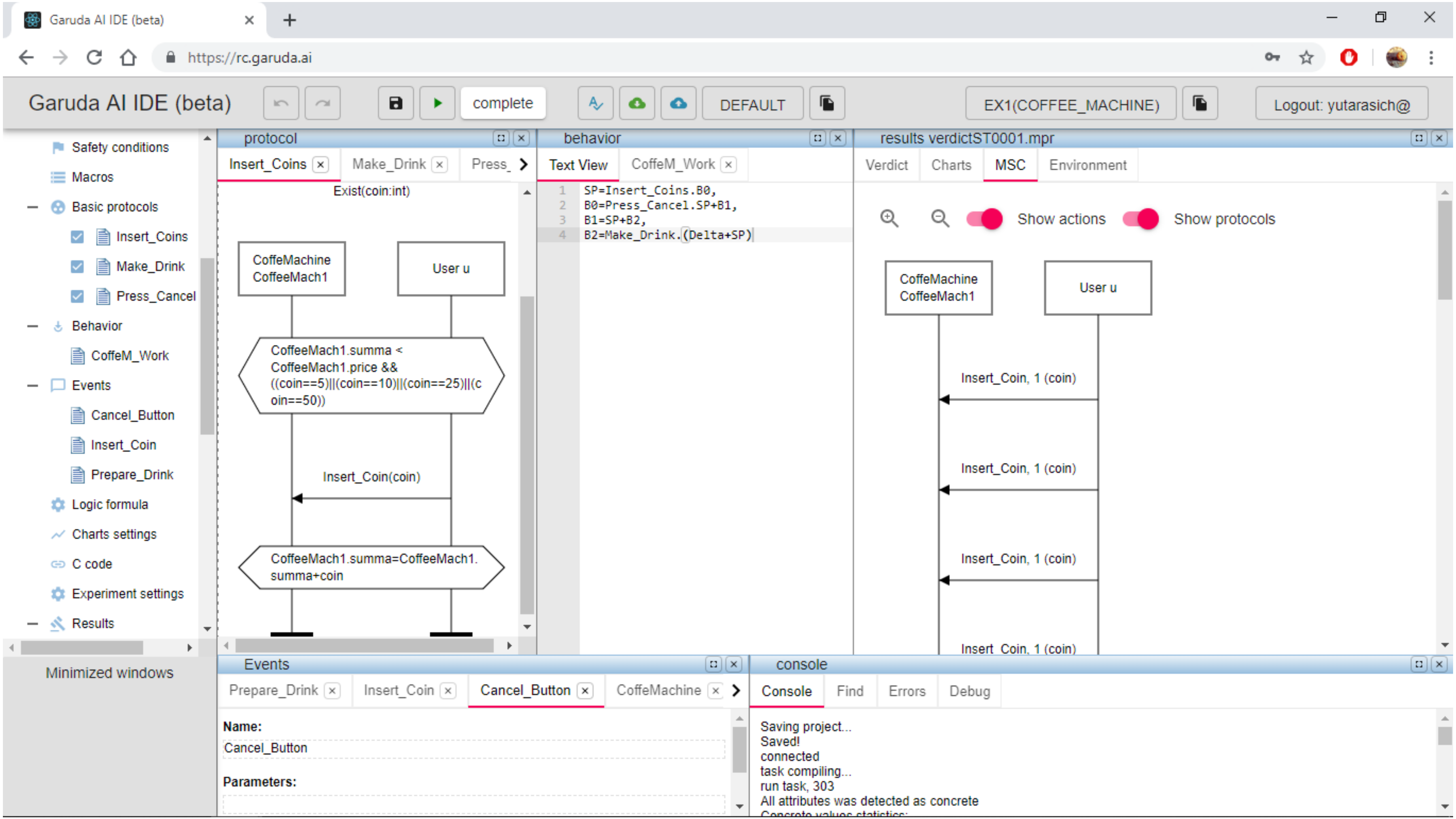
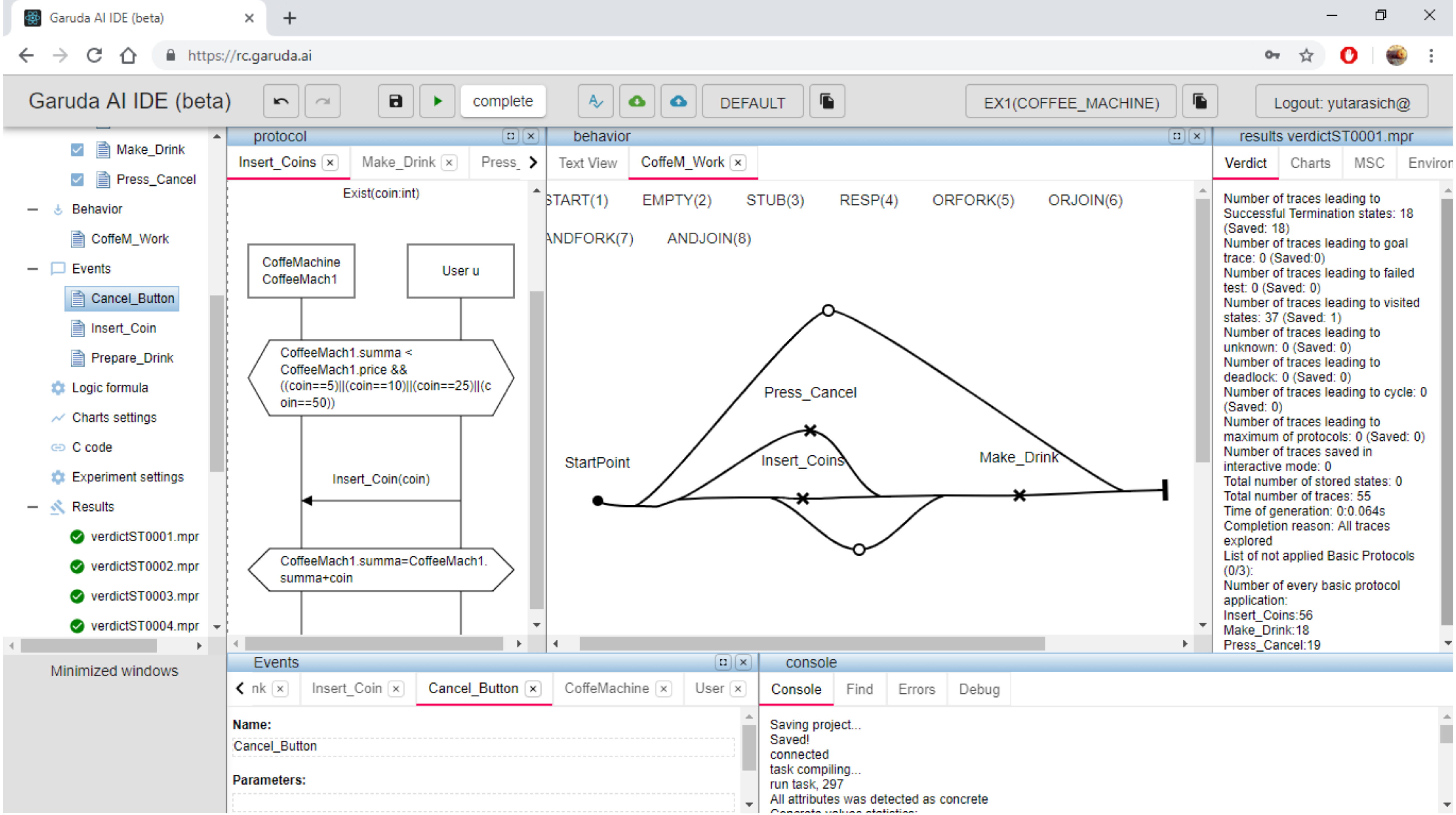
TWO-LEVEL ORGANIZATION IS MORE EFFICIENT:

- Reduce the time of matching;
- Reduce the number of FALSE POSITIVE;
- The accuracy is high


Garuda AI IDE (beta)
https://rc.garuda.ai
Garuda AI IDE (beta)
complete
DEFAULT
EX1(COFFEE_MACHINE)
Logout: yutarasich@
Safety conditions
Macros
Basic protocols
Insert_Coins
Make_Drink
Press_Cancel
Behavior
CoffeM_Work
Events
Cancel_Button
Insert_Coin
Prepare_Drink
Logic formula
Charts settings
C code
Experiment settings
Results
Minimized windows
protocol
Insert_Coins
Make_Drink
Press_
Exist(coin:int)
CoffeMachine CoffeeMach1
User u
CoffeeMach1.summa < CoffeeMach1.price && ((coin==5)||(coin==10)||(coin==25)||(coin==50))
Insert_Coin(coin)
CoffeeMach1.summa=CoffeeMach1.summa+coin
behavior
Text View
CoffeM_Work
SP=Insert_Coins.B0,
B0=Press_Cancel.SP+B1,
B1=SP+B2,
B2=Make_Drink.(Delta+SP)
results verdictST0001.mpr
Verdict
Charts
MSC
Environment
Show actions
Show protocols
CoffeMachine CoffeeMach1
User u
Insert_Coin, 1 (coin)
Insert_Coin, 1 (coin)
Insert_Coin, 1 (coin)
Insert_Coin, 1 (coin)
Events
Prepare_Drink
Insert_Coin
Cancel_Button
CoffeMachine
Name:
Cancel_Button
Parameters:
console
Console
Find
Errors
Debug
Saving project...
Saved!
connected
task compiling...
run task, 303
All attributes was detected as concrete



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Insert_Coin
Prepare_Drink
Logic formula
Charts settings
C code
Experiment settings
Results
verdictST0001.mpr
verdictST0002.mpr
verdictST0003.mpr
verdictST0004.mpr
Minimized windows
protocol
Insert_Coins
Make_Drink
Press_
Exist(coin:int)
CoffeMachine CoffeeMach1
User u
CoffeeMach1.summa < CoffeeMach1.price && ((coin==5)||(coin==10)||(coin==25)||(coin==50))
Insert_Coin(coin)
CoffeeMach1.summa=CoffeeMach1.summa+coin
behavior
Text View
CoffeM_Work
START(1)
EMPTY(2)
STUB(3)
RESP(4)
ORFORK(5)
ORJOIN(6)
ANDFORK(7)
ANDJOIN(8)
Press_Cancel
StartPoint
Insert_Coins
Make_Drink
results verdictST0001.mpr
Verdict
Charts
MSC
Environ
Number of traces leading to Successful Termination states: 18 (Saved: 18)
Number of traces leading to goal trace: 0 (Saved:0)
Number of traces leading to failed test: 0 (Saved: 0)
Number of traces leading to visited states: 37 (Saved: 1)
Number of traces leading to unknown: 0 (Saved: 0)
Number of traces leading to deadlock: 0 (Saved: 0)
Number of traces leading to cycle: 0 (Saved: 0)
Number of traces leading to maximum of protocols: 0 (Saved: 0)
Number of traces saved in interactive mode: 0
Total number of stored states: 0
Total number of traces: 55
Time of generation: 0:0.064s
Completion reason: All traces explored
List of not applied Basic Protocols (0/3):
Number of every basic protocol application:
Insert_Coins:56
Make_Drink:18
Press_Cancel:19
Events
nk
Insert_Coin
Cancel_Button
CoffeMachine
User
Name:
Cancel_Button
Parameters:
console
Console
Find
Errors
Debug
Saving project...
Saved!
connected
task compiling...
run task, 297
All attributes was detected as concrete

THANK YOU FOR ATTENTION

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