

The "Blue Team" Cyber-Defense Orchestrator

AI Planning & Reasoning Project - A.Y. 2025/2026

PRESENTED BY



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Motivation & Goals

Context and Goal of the Blue Team Agent

⚠ THE CONTEXT: MODERN THREATS

Corporate networks face constant automated threats like **Worms** and **Ransomware**. Manual intervention is often too slow to prevent their spread.

🛡 THE SOLUTION: "BLUE TEAM" AGENT

- 1 **Monitoring:** Real-time health analysis.
- 2 **Planning (PDDL):** Generation of remediation strategy.
- 3 **Reacting (IndiGolog):** Autonomous response to intrusions.

◎ MAIN OBJECTIVE

Maintain the CIA Triad:

Confidentiality: Protect sensitive data on Database Servers.

Integrity: Ensure nodes remain 'Clean' and free of malware.

Availability: Minimize service downtime during containment and remediation.



Domain Taxonomy

IT Environment Modeling: Entities and Dynamics



NETWORK NODES

Workstations

HIGH RISK

Low-priority user devices but high risk of initial infection.

DB Servers

CRITICAL

Central hubs containing sensitive data. Their integrity is critical.

Web Servers

Public interfaces. They depend on DB Servers to operate correctly.



ADVERSARIES

Worm

Self-replicating malware that spreads rapidly and linearly across connected nodes.

Ransomware

Encrypts data, making it inaccessible. Requires expensive backups or decryption keys.

Agent Actions

DEFENSE ACTIONS

1. **scan(Node)**:

- Identifies the infection status of a node

2. **isolate_node(Node)**:

- Prevents malware spread but reduces service availability
- Degrades services of dependent nodes (ADL conditional effect)

3. **patch(Node)**:

- Removes malware and fixes vulnerabilities

4. **restore_backup(Node)**:

- Recovers encrypted data from backups

5. **reconnect(Node)**:

- Brings isolated node back online

SUBNET MANAGEMENT ACTIONS

6. **restart_router(Subnet)**:

- Restarts network router for a subnet
- Effect: Brings subnet back online

7. **verify_connection(Subnet)**:

- Confirms subnet connectivity after restart
- Always possible (no preconditions)

8. **wait_step**:

- Advances the simulation by one time step
- Used in monitoring loops between scans

Environment Dynamics & Constraints

NUMERIC CONSTRAINTS (RESOURCES)

To simulate real-world limitations, we introduce numeric variables:

Network Bandwidth: Limited throughput capacity per time-step. Heavy operations like Restore require available bandwidth to be executed.

Max Bandwidth Limit: Fixed threshold that defines the network's maximum operation capacity.

Downtime Costs: Each node has a priority weight and isolating a node increases downtime cost by its weight
• High-value nodes (CoreServer: 100) vs. workstations (10)

OPTIMIZATION CHALLENGE

The core complexity lies in the ***Security vs. Availability trade-off:***

Isolating threats prevents spread but halts business operations.

Keeping services running risks further infection.

Goal: Minimize downtime costs while maintaining integrity.

PDDL Formalization

State Predicates and Cost Functions

KEY PREDICATES

STRIPS

ADL

;; Network Topology & State

```
(connected ?n1 ?n2)
(infected ?n ?m)
(isolated ?n)
(clean ?n)
```

;; ADL Features (Conditional Effects)

```
(depends-on ?n1 ?n2)
(service-degraded ?n)
```

NUMERIC FUNCTIONS

NUMERIC

;; Resource Constraints

```
(bandwidth-used) // total bandwidth consumed by actions
(max-bandwidth)
;; Optimization Metrics
(downtime-cost) // accumulated cost of service interruption
```

;; Static Properties

```
(priority-weight ?node)
```

// asset value(es. DB=100, PC=10)

ADL Note: We use depends-on to model fault propagation (e.g. if the DB is isolated, the WebServer is service-degraded).

Global Optimization: The planner optimizes exclusively for (downtime-cost). Bandwidth is tracked as a resource consumption but is not part of the minimization metric in this instance.

Heuristics Strategy

Comparison of Fast Downward Approaches



Blind Search

BASELINE

Uninformed search (Breadth-First).
Explores the state space without any
heuristic guidance.

- ✓ No computational overhead $h(n)$
- ✓ Useful for measuring complexity
- ✗ Exponential node expansion

REFERENCE



h_{add}

ADDITIVE

"Satisfying" heuristic. Adds the costs of
the subgoals, ignoring negative
interactions.

- ✓ High search speed
- ✓ Strong guidance towards the goal
- ✗ Not admissible

MAX SPEED



h_{max}

ADMISSIBLE

Conservative heuristic. Considers only
the maximum cost among the parallel
subgoals.

- ✓ Guarantees Optimality
- ✓ Admissible (always underestimation)
- ✗ Less informative than h_{add}

OPTIMAL PLAN

Problem 1 - Worm Outbreak

Linear Scenario (STRIPS)

TOPOLOGY & STATE



⚠ THREAT ACTIVE: NODE A

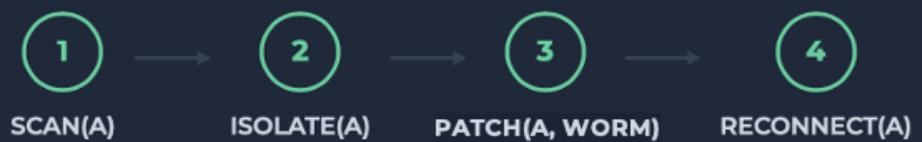
CONTEXT

The network has a simple linear topology. Node A has been infected with a worm. Without intervention, the malware will sequentially propagate to Node B and then to Node C. The agent must act quickly to contain the threat and clean up the system.

PDDL GOAL

```
(:goal (and
  (clean nodeA)
  (clean nodeC) ; Ensure spread stopped
  (not (isolated nodeA)) ; Restore Service
))
```

EXPECTED PLAN



Logic: Isolation is a necessary precondition for the **patch** action, preventing spread during remediation.

Problem 1 - Experimental Results

"Worm Outbreak" - Linear Topology

Blind Search

BASELINE



<input checked="" type="checkbox"/> Status	Solved (Opt)
Plan Cost	4
Expanded	6
Evaluated	6
Time (s) (avg on 10 runs)	0.45256
Initial h	1

h_{add}

ADDITIVE



<input checked="" type="checkbox"/> Status	Solved (Opt)
Plan Cost	4
Expanded	5
Evaluated	6
Time (s) (avg on 10 runs)	0.48216
Initial h	3

h_{max}

ADMISSIBLE



<input checked="" type="checkbox"/> Status	Solved (Opt)
Plan Cost	4
Expanded	5
Evaluated	6
Time (s) (avg on 10 runs)	0.39170
Initial h	2

OPTIMAL PLAN

Scan(A) → Isolate(A) → Patch(A) → Reconnect(A)

INSIGHT

The h_{add} and h_{max} heuristics are more efficient than blind search, expanding 1 fewer node and leading immediately to the goal.

Problem 2 - The Critical Hub (ADL)

Dependency Management and Conditional Effects

STAR TOPOLOGY



ADL SCENARIO & CHALLENGE

A **Central Database** serves two Web Servers. If the DB is isolated for maintenance or defense, all dependent nodes automatically become **service-degraded**.
Challenge: The agent must understand that isolating the DB has an immediate collateral "cost" on the entire dependent network.

</> PDDL: CONDITIONAL EFFECTS

```
(:action isolate
  :parameters (?n - node)
  :effect (and
    (isolated ?n) (not(connected ?n ?n)))
    ;Conditional Effect
    (forall (?dep - node)
      (when (depends-on ?dep ?n)
        (service-degraded ?dep)))))
```

ADL FEATURE

Forall Logic: This construct checks all network nodes in a single step. If a dependency exists (`depends-on`), the state of the dependent node is altered.

END GOAL

- ✓ Restore full operation (no degraded nodes).
- ✓ Ensure that the DB is clean and reconnected.

The planner must understand that reconnecting DB *automatically* restores dependent services via the ADL forall effect

Problem 2 - Experimental Results

Critical Hub (ADL Scenario)

	
Blind	
UNINFORMED	
Status	Solved
Plan Cost	4
Expanded	6
Evaluated	6
Time (avg on 10 runs)	0.40232
Initial h	1

	
h_add	
ADDITIVE	
Status	Solved
Plan Cost	4
Expanded	5
Evaluated	6
Time (avg on 10 runs)	0.41900
Initial h	3

	
h_max	
ADMISSIBLE	
Status	Solved
Plan Cost	4
Expanded	5
Evaluated	6
Time (avg on 10 runs)	0.40324
Initial h	2

Results Analysis

The planner correctly interpreted the ADL constraints: it inserted the reconnect(db) action as a mandatory final step. Without reconnection, the goal would not have been met due to conditional effects. H_hadd provided the estimate closest to the actual cost (3 vs. 4)

PLAN SEQUENCE FOUND
scan → isolate → patch → reconnect

Problem 3 - Ransomware Crisis

Numeric Planning

COST ANALYSIS AND COMPLEXITY



COMPLEX SCENARIO

The system is facing a ransomware infection. Unlike worms, data is encrypted. Restoring from backups is safe but requires high bandwidth availability (20 BW), which may exceed network capacity if not managed.

PLANNER TARGET

**ENHSP-20 (numeric
fluents and metrics)**

OBJECTIVE

Minimize Overall Cost

OBJECTIVE FUNCTION (METRIC)

```
(:metric minimize (: (downtime-cost)) )
```

The planner focuses on minimizing downtime-cost. Bandwidth usage is tracked but does not influence the optimization score directly."

NUMERICAL CONSTRAINTS

ACTION COSTS (BANDWIDTH)

action: Patch	check <= MAX_BANDWIDTH	5 BW
---------------	------------------------	------

action: Restore	check <= MAX_BANDWIDTH	20 BW
-----------------	------------------------	-------

PRIORITY TO KEEP THE COST LOW



Problem 3: Optimization Logic

Balancing Resource Costs VS Asset Priority

RESOURCE CONSTRAINTS (BANDWIDTH)

Constraint Logic: Bandwidth is modeled as a **Capacity Check**.

Patch (5 BW): Feasible if the capacity is enough

Restore (20 BW): Feasible only if sufficient capacity exists.
Note: The planner filters out actions that exceed the (max-bandwidth) threshold.

ASSET PRIORITY (DOWNTIME PENALTY)

- Defined in *instance3-ransomware-problem.pddl*:
- **CoreServer**: Weight 100 (Critical).
- **Workstations**: Weight 10 (Low Priority).
- The objective function minimize (downtime-cost) drives the decision. High-priority nodes (CoreServer=100) force the planner to find the quickest valid repair plan available within bandwidth limits

Problem 3 - Experimental Results

"Ransomware Crisis"

Blind Search

BASELINE-> STATUS: SOLVED

<input checked="" type="checkbox"/> Cost	110
Plan Length	8
Expanded	79
<input type="checkbox"/> Evaluated	152
<input type="checkbox"/> Time (s) avg on 10 runs	0.175
<input type="checkbox"/> Initial h	0



h_add

ADDITIVE-> STATUS: SOLVED

<input checked="" type="checkbox"/> Cost	110
Plan Length	8
Expanded	18
<input type="checkbox"/> Evaluated	60
<input type="checkbox"/> Time (s) avg on 10 runs	0.208
<input type="checkbox"/> Initial h	210



h_max

ADMISSIBLE -> STATUS: SOLVED

<input checked="" type="checkbox"/> Cost	110
Plan Length	9
Expanded	21
<input type="checkbox"/> Evaluated	69
<input type="checkbox"/> Time (s) avg on 10 runs	0.209
<input type="checkbox"/> Initial h	100



OPTIMAL PLAN

```
Scan(Core)-> Isolate(Core)-> Patch(Core)-> Scan(WS1)->Isolate(WS1)  
->Restore(Core)->Patch(WS1)->Reconnect(Core)
```

INSIGHT

All heuristics found the minimal cost (110), proving the planners correctly prioritized the CoreServer (Weight 100). h_add was extremely efficient, expanding only 18 nodes compared to 79 for Blind search, demonstrating strong guidance in the numeric state space.

IndiGolog - Intelligent Agent

Control Architecture & OODA Loop



Active Sensing

The agent actively queries the simulation status to update its knowledge base.

```
execute(scan(N), Result)
```

! Exogenous Events

The environment is dynamic. Events such as **alert_intrusion**, **service_crash** and **network_reset** occur asynchronously and require immediate handling

⚡ Prioritized Concurrency

Use constructs to handle high-priority interruptions, suspending routine tasks for emergencies.

TECH STACK

SWI-Prolog

IndiGolog

IndiGolog Domain Model

Topology, Fluents, and Causal Laws (domain.pl)

NETWORK TOPOLOGY

-  **db_server** Central hub (critical)
-  **web_server_1** Depends on db_server
-  **web_server_2** Depends on db_server
-  **Workstation_a** Endpoint device

SUBNETS & DEPENDENCIES

```
subnet(subnet_alpha). subnet(subnet_beta).
```

PRIMITIVE FLUENTS

```
infected(N), clean(N), isolated(N)  
subnet_online(S), service_degraded(N)  
% Initial state  
initially(clean(N), true) :- node(N).  
initially(infected(N), false) :- node(N).
```

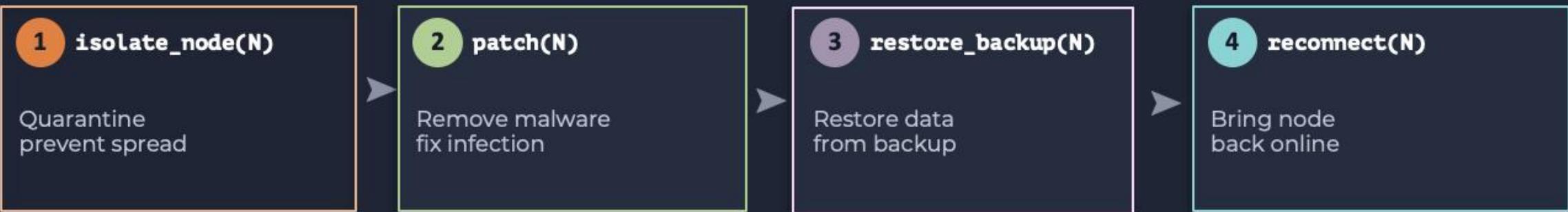
CAUSAL LAWS

```
% ADL: isolating DB degrades dependents  
causes_val(isolate_node(DB),  
          service_degraded(WS), true, depends_on(WS,DB)).  
  
% Reconnecting restores services  
causes_val(reconnect(DB),  
  
% Exogenous effects service_degraded(WS), false, depends_on(WS,DB)).  
causes_val(alert_intrusion(N), infected(N), true, true).  
causes_val(service_crash(S), subnet_online(S), false, true).
```

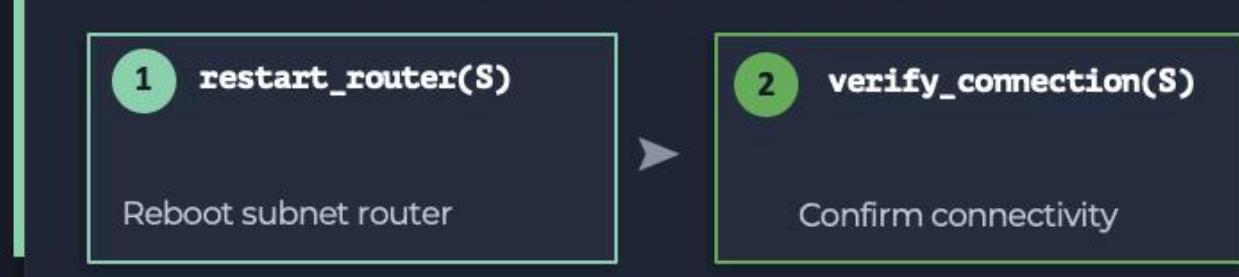
Recovery Procedures

Building blocks used by all 3 controllers (agent_logic.pl)

NODE RECOVERY: recover_node_procedure(N)



SUBNET RECOVERY: recover_subnet_procedure(S)



Active Monitoring: monitor_network

Scanning loop used by Passive and Reactive-Poll controllers

PROLOG SOURCE

```
proc(monitor_network,  
    [  
        scan(db_server),  
        wait_step,  
        scan(web_server_1),  
        wait_step,  
        scan(web_server_2),  
        wait_step  
    ]  
).
```

SENSING MECHANISM

Each `scan(N)` is a sensing action. The engine calls `execute(scan(N), Result)` which returns **true/false** for the fluent `infected(N)`.

ROLE IN EACH CONTROLLER

Passive: Full cycle, THEN checks fluents.

Reactive: NOT used — waits for exogenous events.

Reactive-Poll: Checks fluents AFTER each scan.

Controller 1: Passive

Scan ALL → Check ALL → React → Loop

</> CODE STRUCTURE

```
proc(control(passive),  
while(true, [  
monitor_network, % Phase 1: scan all  
if(infected(db_server), % Phase 2: react  
recover_node_procedure(db_server), no_op),  
if(infected(web_server_1),  
recover_node_procedure(web_server_1), no_op),  
if(infected(web_server_2),  
recover_node_procedure(web_server_2), no_op),  
if(infected(workstation_a),  
recover_node_procedure(workstation_a), no_op),  
recover_all_subnets % Phase 3: subnets  
])  
).
```

* LOGIC BREAKDOWN

Timeline Example

t=0 scan(db_server) → clean
t=1 scan(web_server_1) → clean
⚡ INFECTION db_server!
t=2 scan(web_server_2) → clean ← continue
t=3 infected(db_server)? → TRUE!
t=3 ↗ isolate → patch → restore_backup →
reconnect ↘
t=7 ↳ RECOVERY COMPLETED
—————
t=8 ↴ loop
...

Limitations

Waits until the scan loop is finished

Controller 2: Reactive

Event-driven — prioritized_interrupts

CODE STRUCTURE

```
proc(control(reactive), [prioritized_interrupts([  
  
    % Priority 1: infected node → recovery  
    interrupt(n, infected(n),  
              recover_node_procedure(n)),  
  
    % Priority 2: subnet down → recovery subnet  
    interrupt(neg(subnet_online(subnet_alpha))),  
              recover_subnet_procedure(subnet_alpha)),  
    interrupt(neg(subnet_online(subnet_beta))),  
              recover_subnet_procedure(subnet_beta)),  
  
    % Priority 3: wait  
    interrupt(true, ?(wait_exog_action))  
])]).
```

LOGIC BREAKDOWN

Timeline Example

t=0 → idle (wait_exog_action)
⚡ INFECTION db_server!
t=1 Priority 1: infected(db_server)? → TRUE!
t=1 ↴ isolate → patch → restore_backup →
reconnect ↴
t=5 ↴ RECOVERY COMPLETED

t=5 re-eval interrupt → everything ok → idle

Limitations

Depends only on prioritized_interrupts. We
don't have any active monitoring.

Advantages

No latency, the interrupt starts immediately

Controller 3: Reactive Pool

Scan one → Check all → React → Next node → Repeat

</> CODE STRUCTURE

```
proc(control(reactive_poll),  
     while(true,  
     [  
      scan(db_server),  
      recover_any_infected,  
      recover_all_subnets,  
      wait_step,  
  
      scan(web_server_1),  
      recover_any_infected,  
      recover_all_subnets,  
      wait_step,  
  
      scan(web_server_2),  
      recover_any_infected,  
      recover_all_subnets,  
      wait_step  
    ]  
  )  
).
```

* LOGIC BREAKDOWN

Timeline Example

t=0 scan(db_server) → clean
t=1 check all → tutto ok
⚡ INFECTION db_server!
t=2 scan(web_server_1) → clean
t=3 check all: infected(db_server)? → TRUE!
t=3 ↴ isolate → patch → restore_backup →
reconnect ↴
t=7 ↴ RECOVERY COMPLETED
—————
t=8 scan(web_server_2) → clean → check → ok
t=9 ↴ loop

Limitations

Overhead, latency of 2 steps

Advantages

Doesn't require prioritized_interrupts.

Graphical Interface

CYBER-DEFENSE ORCHESTRATOR

⌚ Waiting for Prolog...

NETWORK STATUS

DB SERVER ● CLEAN	WEB SERVER 1 ● CLEAN	WEB SERVER 2 ● CLEAN	WORKSTATION A ● CLEAN
SUBNET ALPHA ● ONLINE	SUBNET BETA ● ONLINE		

TRIGGER EXOGENOUS EVENTS

- 🔴 INTRUSION ALERT
 - ⚠ db_server
 - ⚠ web_server_1
 - ⚠ web_server_2
 - ⚠ workstation_a
- ⚡ SERVICE CRASH
 - ⚡ subnet_alpha
 - ⚡ subnet_beta
- ⟳ NETWORK RESET

EVENT LOG

```
[20:59:55] Server listening on port 9999...
```

Reasoning Task 1: Legality Check

PROJECTION QUERY

PROLOG

SITCALC

EXECUTION OUTPUT

```
% Precondition (domain.pl)
poss(restore_backup(N), and(isolated(N),
clean(N))) :- node(N).
```

```
% Initial state
initially(clean(N), true) :- node(N).
initially(isolated(N), false) :- node(N).
initially(infected(N), false) :- node(N).
...
```

==> TASK 1: LEGALITY ==>

Testing preconditions of restore_backup

1a. restore_backup(db_server) without
isolation... BLOCKED (correct: not
isolated)

1b. restore_backup(db_server) when
infected... BLOCKED (correct: not clean)

1c. restore_backup(db_server) when
isolated+clean... ALLOWED (correct)
...

Reasoning Task 2: Temporal Projection

Prediction of Future State with Situation Calculus

PROJECTION QUERY

PROLOG SITCALC

```
% Derived fluent (domain.pl)
service_available(Node, History) :-  
node(Node),  
holds(neg(isolated(Node)), History),  
holds(neg(service_degraded(Node)), History).  
% Test (reasoning_tests.pl)  
ActionList = [isolate_node(db_server)],  
holds(service_degraded(web_server_1), ActionList)  
% → TRUE (ADL conditional effect)  
holds(isolated(db_server), ActionList)  
% → TRUE  
\+ service_available(web_server_1, ActionList)  
% → FALSE (correct: dependency breaks service)
```

EXECUTION OUTPUT

CONSOLE

```
After isolate_node(db_server):  
Query: service_available(web_server_1)?  
  
service_degraded(web_server_1)? TRUE  
(correct: ADL conditional effect)  
  
isolated(db_server)? TRUE  
  
service_available(web_server_1)? FALSE  
(correct: dependency breaks service)
```

Logic: The test verifies that `service_degraded(web_server_1)` becomes true after `isolate_node(db_server)` thanks to the conditional effect in ``causes_val``

Reasoning Task 3: Planning

</> HIGH-LEVEL PROGRAM

PROLOG

INDIGOLOG

```
% Procedure (agent_logic.pl)
proc(recover_subnet_procedure(S),
[
  restart_router(S),
  verify_connection(S)
]
).

% Test (reasoning_tests.pl)
InitialHistory = [service_crash(subnet_alpha)],
findpath(recover_subnet_procedure(subnet_alpha),
InitialHistory, Path)
% → FOUND
% Plan: [restart_router(subnet_alpha),
verify_connection(subnet_alpha)]
...
```

> EXECUTION RESULT

SUCCESS

==> TASK 3: PLANNING ==>

Scenario: subnet_alpha is offline

Goal: Find recovery plan

OUTPUT:

```
> Plan Found: [restart_router(subnet_alpha),
  verify_connection(subnet_alpha)]
```

Full Execution Trace

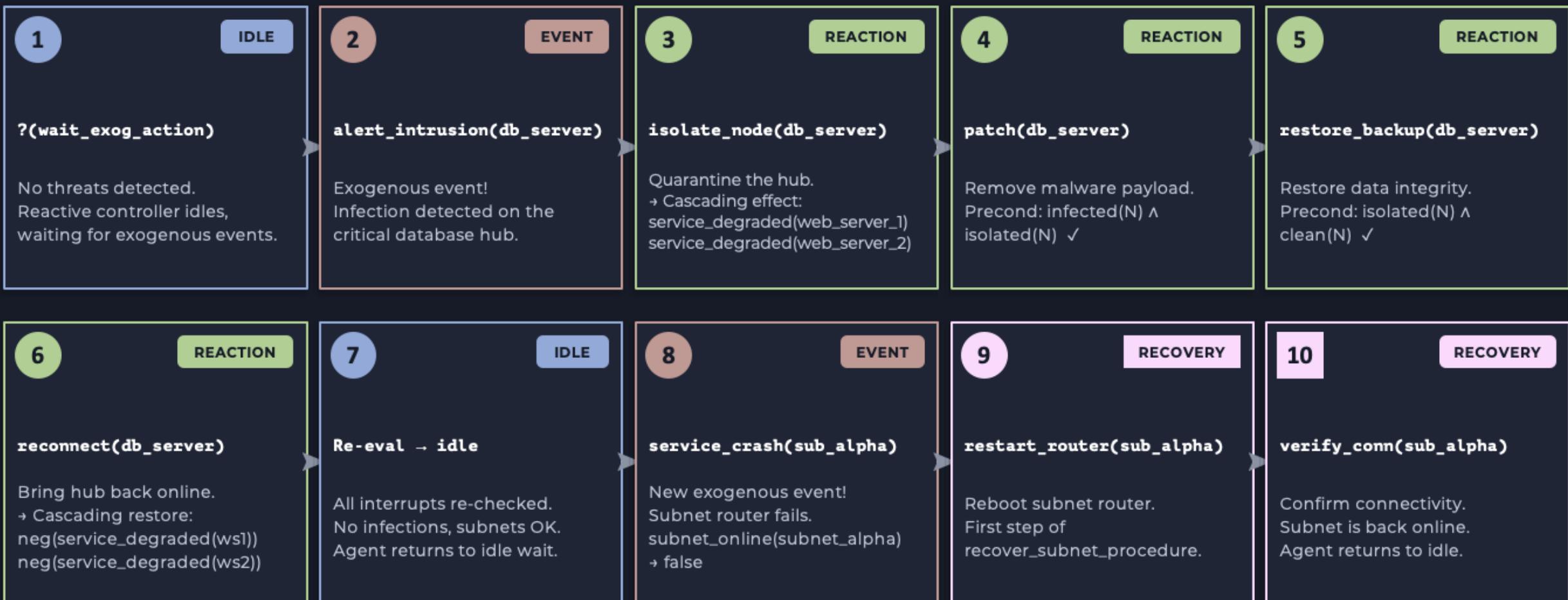
Reactive Controller Demonstration (IndiGolog)

Routine

Event

Recovery

Subnet



Key: 4-step node recovery (`isolate` → `patch` → `restore_backup` → `reconnect`) | ADL cascade on `isolate` & `reconnect` | Zero-latency: reactive fires immediately on event

Conclusion & Future Works

Project Summary and Next Steps

ACHIEVEMENTS

✓ Robust Modeling

ADL conditional effects and numeric constraints across PDDL and IndiGolog domains.

✓ Heuristic Optimization

Demonstrated h_add/h_max efficiency across 3 problem instances.

✓ 3 Control Strategies

Passive, Reactive, Reactive-Poll with different latency/complexity trade-offs.

✓ Complete OODA Loop

Working IndiGolog agent with sensing, interrupts, and dynamic plan execution.

FUTURE WORK

⚡ Real-World Integration

Connect with scanning tools (e.g., NMAP) to dynamically populate the KB.

⚡ Probabilistic Scenarios

Stochastic Games to model action failures and intelligent adversaries.

⚡ Enterprise Scalability

Testing on large-scale topologies with hundreds of heterogeneous nodes.

⚡ Multi-Agent Coordination

Multiple IndiGolog agents across different network segments.

Thanks for the attention

Sapienza Università di Roma · Planning & Reasoning Project 2025/2026