UNIVERSITY PROJECT

The "Blue Team" Cyber-Defense Orchestrator

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

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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

DYNAMIC STATES

Nodes transition between specific operational status based on events and agent actions:

Clean: Normal operation.

Data Encrypted: Files locked by ransomware

Infected: Compromised by malware (Worms or Ransomware).

Isolated: Disconnected to prevent spread (quarantine).

Service Degraded: Dependent services affected to hub isolation

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)
```

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

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)
```

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

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

1. SCAN(A)
2. ISOLATE(A)
3. PATCH(A, WORM)
4. RECONNECT(A)

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

Status	Solved (Opt)
Plan Cost	4
Expanded	6
Evaluated	6
Time (s) (avg on 10 runs)	0.45256
Initial h	1

h_add

ADDITIVE

Status	Solved (Opt)
Plan Cost	4
Expanded	5
Evaluated	6
Time (s) (avg on 10 runs)	0.48216
Initial h	3

h_max

ADMISSIBLE

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

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.

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.

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 considtional effects. H_hadd provided the estimate closest to the actual cost (3 vs. 4)

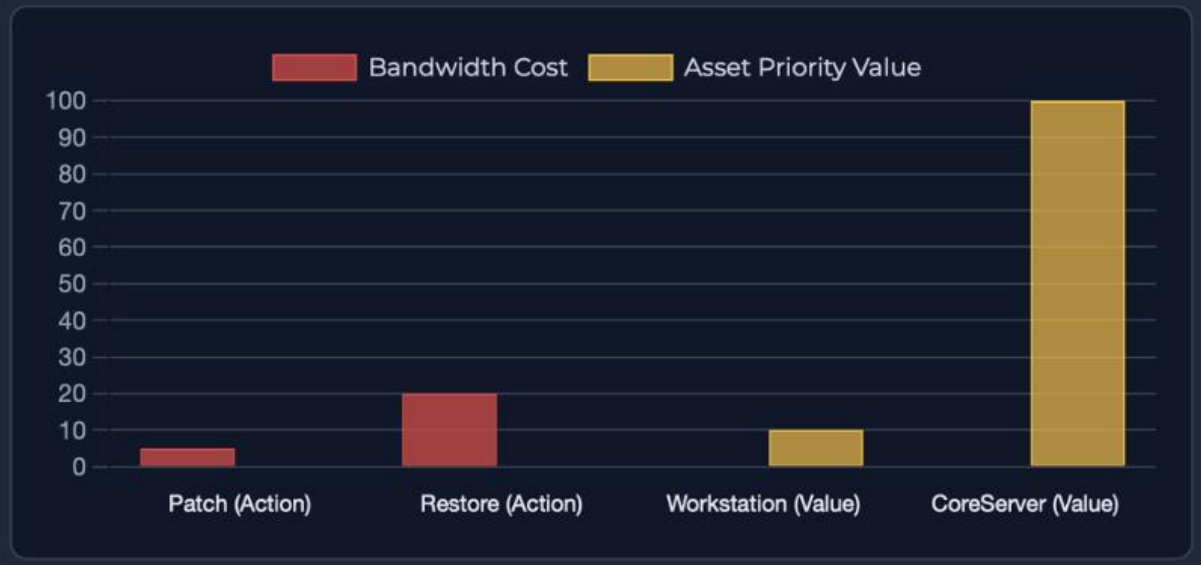
PLAN SEQUENCE FOUND

`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

CoreServer	100
Workstation	10

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

Cost	110
Plan Length	8
Expanded	79
Evaluated	152
Time (s) avg on 10 runs	0.175
Initial h	0

h_add

ADDITIVE-> STATUS: SOLVED

Cost	110
Plan Length	8
Expanded	18
Evaluated	60
Time (s) avg on 10 runs	0.208
Initial h	210

h_max

ADMISSIBLE -> STATUS: SOLVED

Cost	110
Plan Length	9
Expanded	21
Evaluated	69
Time (s) avg on 10 runs	0.209
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)

1. **isolate_node(N)**
   Quarantine
   prevent spread
2. **patch(N)**
   Remove malware
   fix infection
3. **restore_backup(N)**
   Restore data
   from backup
4. **reconnect(N)**
   Bring node
   back online

SUBNET RECOVERY: recover_subnet_procedure(S)

1. **restart_router(S)**
   Reboot subnet router
2. **verify_connection(S)**
   Confirm connectivity

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 untile 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.

Reasoning Task 1: Legality Check

PROJECTION QUERY PROLOG SITCALC

```
% 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).
```

EXECUTION OUTPUT

```
=== 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)
```

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`

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)
```

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

1 IDLE

`?(wait_exog_action)`

No threats detected.
Reactive controller idles,
waiting for exogenous events.

2 EVENT

`alert_intrusion(db_server)`

Exogenous event!
Infection detected on the
critical database hub.

3 REACTION

`isolate_node(db_server)`

Quarantine the hub.
→ Cascading effect:
service_degraded(web_server_1)
service_degraded(web_server_2)

4 REACTION

`patch(db_server)`

Remove malware payload.
Precond: infected(N) ∧
isolated(N) ✓

5 REACTION

`restore_backup(db_server)`

Restore data integrity.
Precond: isolated(N) ∧
clean(N) ✓

6 REACTION

`reconnect(db_server)`

Bring hub back online.
→ Cascading restore:
neg(service_degraded(ws1))
neg(service_degraded(ws2))

7 IDLE

`Re-eval → idle`

All interrupts re-checked.
No infections, subnets OK.
Agent returns to idle wait.

8 EVENT

`service_crash(sub_alpha)`

New exogenous event!
Subnet router fails.
subnet_online(subnet_alpha)
→ false

9 RECOVERY

`restart_router(sub_alpha)`

Reboot subnet router.
First step of
recover_subnet_procedure.

10 RECOVERY

`verify_conn(sub_alpha)`

Confirm connectivity.
Subnet is back online.
Agent returns to idle.

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

Reasoning Task 3: Planning

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