# New Algorithms for Attack Planning

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# Brief presentation

- My company: Core Security Technologies
  - Boston (USA)
    - marketing and sales
  - Buenos Aires (Argentina)
    - research and development
- I have worked in Corelabs since 2000
  - that's the research lab (in Buenos Aires)
  - coordinate research activities (e.g. Bugweek) and publication of advisories
  - focus area: applying Artificial Intelligence techniques to solve problems from the security field

# Outline

- Introduction
- The Attack Model
- Use PDDL and champion planners
- Fast probabilistic algorithms

# Introduction

# Why do we need automation?

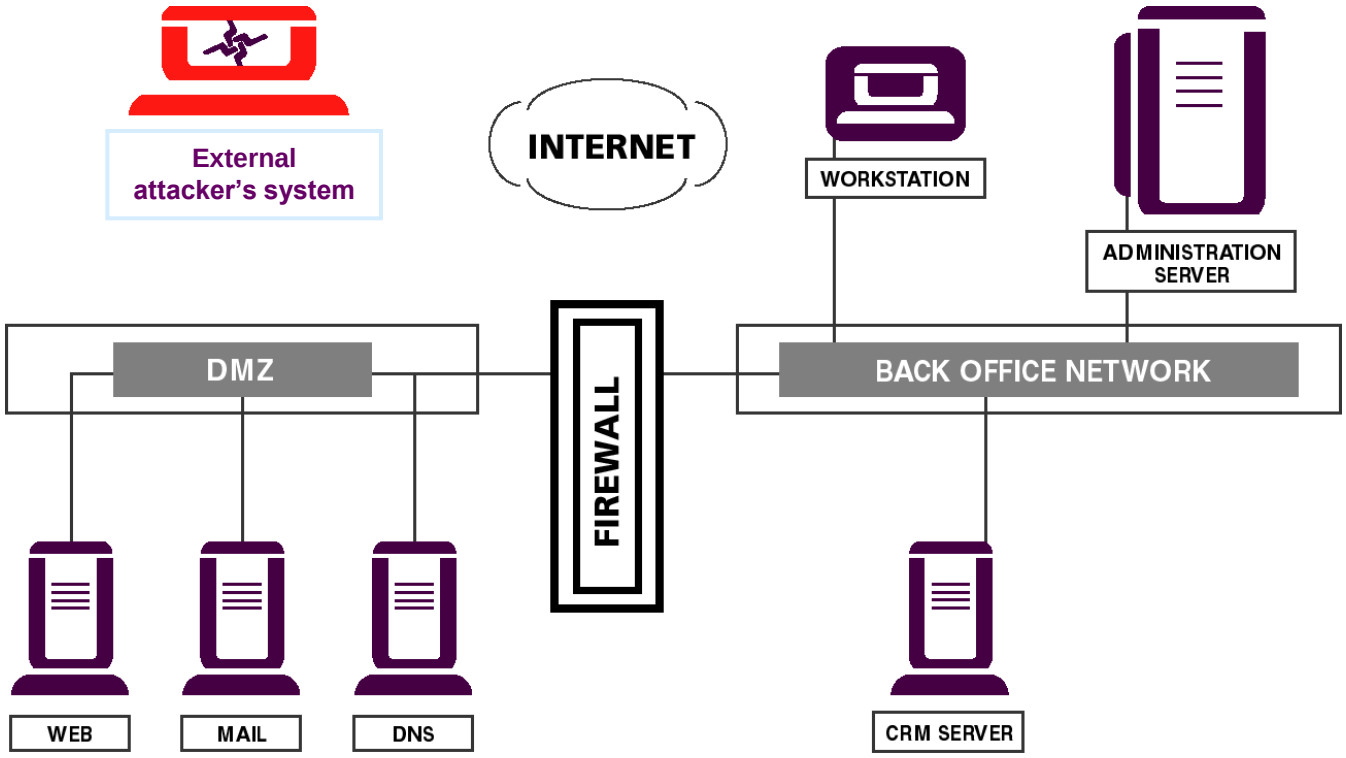
- Evolution of pentesting
  - Attacks are evolving
  - Organizations are evolving
    - technological complexity
    - infrastructure complexity
  - Manual pentesting requires more expertise and time
  - Continuous pentesting

- Pentesting tools are evolving
  - Metasploit (open source)
  - Immunity Canvas and Core Impact (commercial)

# Increase pentesting scale

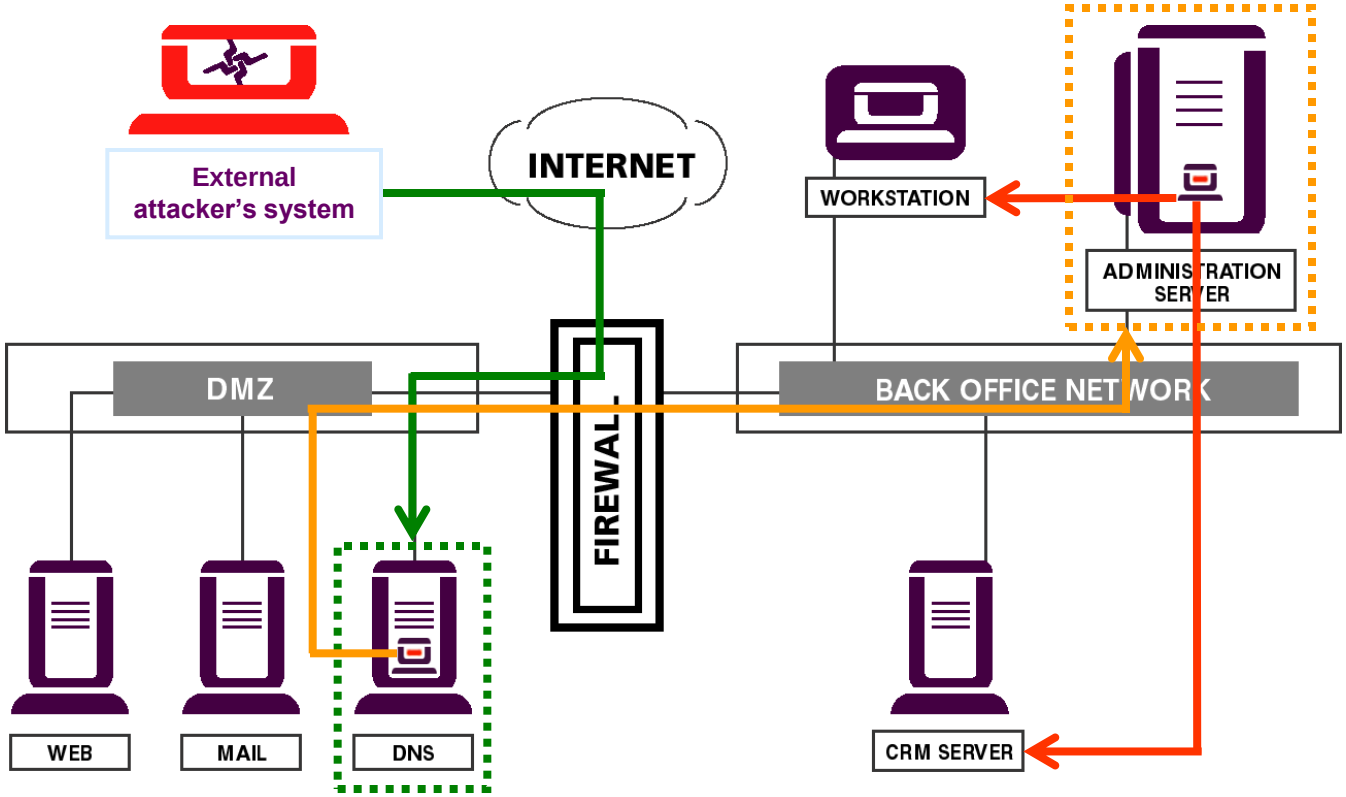
- Example: pentest a network with 200 machines
  - limited human resources
  - bounded time frame
  - pentest mimics attacks which doesn't have those restrictions
- Automating repetitive tasks liberates time for
  - research / creative work
  - training / be up-to-date
  - produce more complex attacks
- Make it more accessible
  - The BOFH can test his own network

# Sample pentest scenario



# Anatomy of a real-world attack

A sophisticated real-world attacker will leverage trust relationships to gain access to more valuable information assets




Base camp

A target server is attacked and compromised

The acquired server is used as vantage point to penetrate the corporate net

Further attacks are performed as an internal user

# The Attack Model

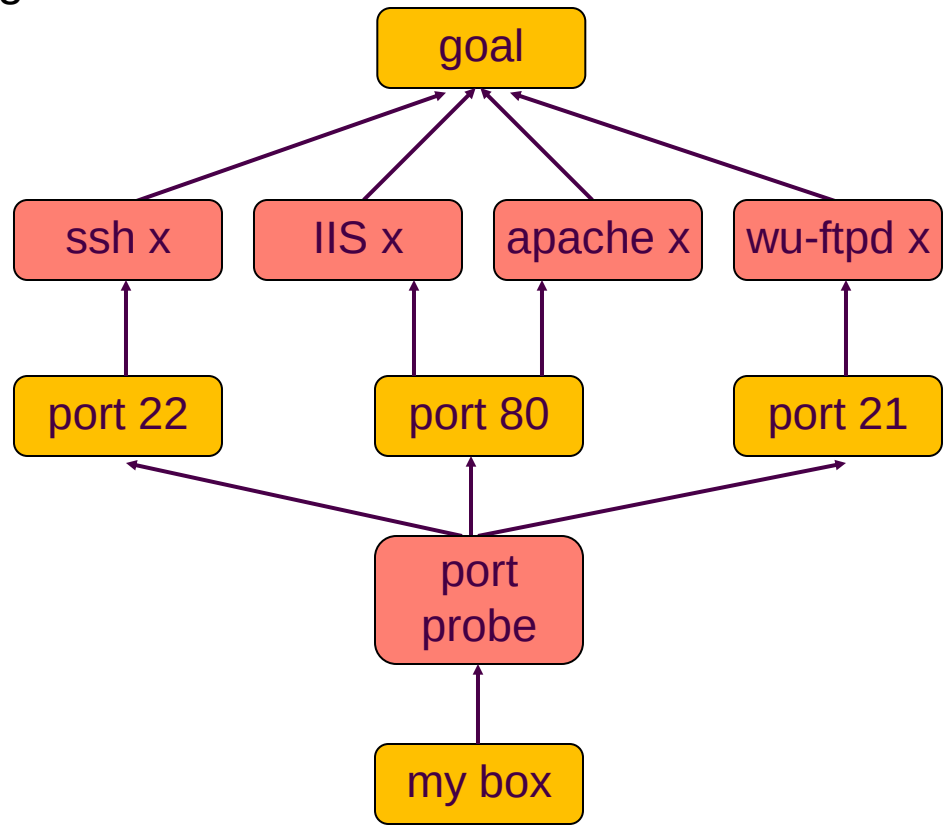
# Example of attack planning

**Goal**: To gain control of any host in target network

**Assets**: Target's IP address
Control of my box
A set of IG tools and exploits

**Actions**:
test if a given port is open (port probe)
exploit ssh (on an OpenBSD)
exploit wu-ftpd (on a Linux)
exploit IIS (on a Windows)
exploit apache (on a Linux)

**Plan**:
Probe only ports 22, 80 and 21.
Probe port 80 first!
As soon as a port is found open, run an exploit.
Keep probing other ports only if exploit fails.



# The model components

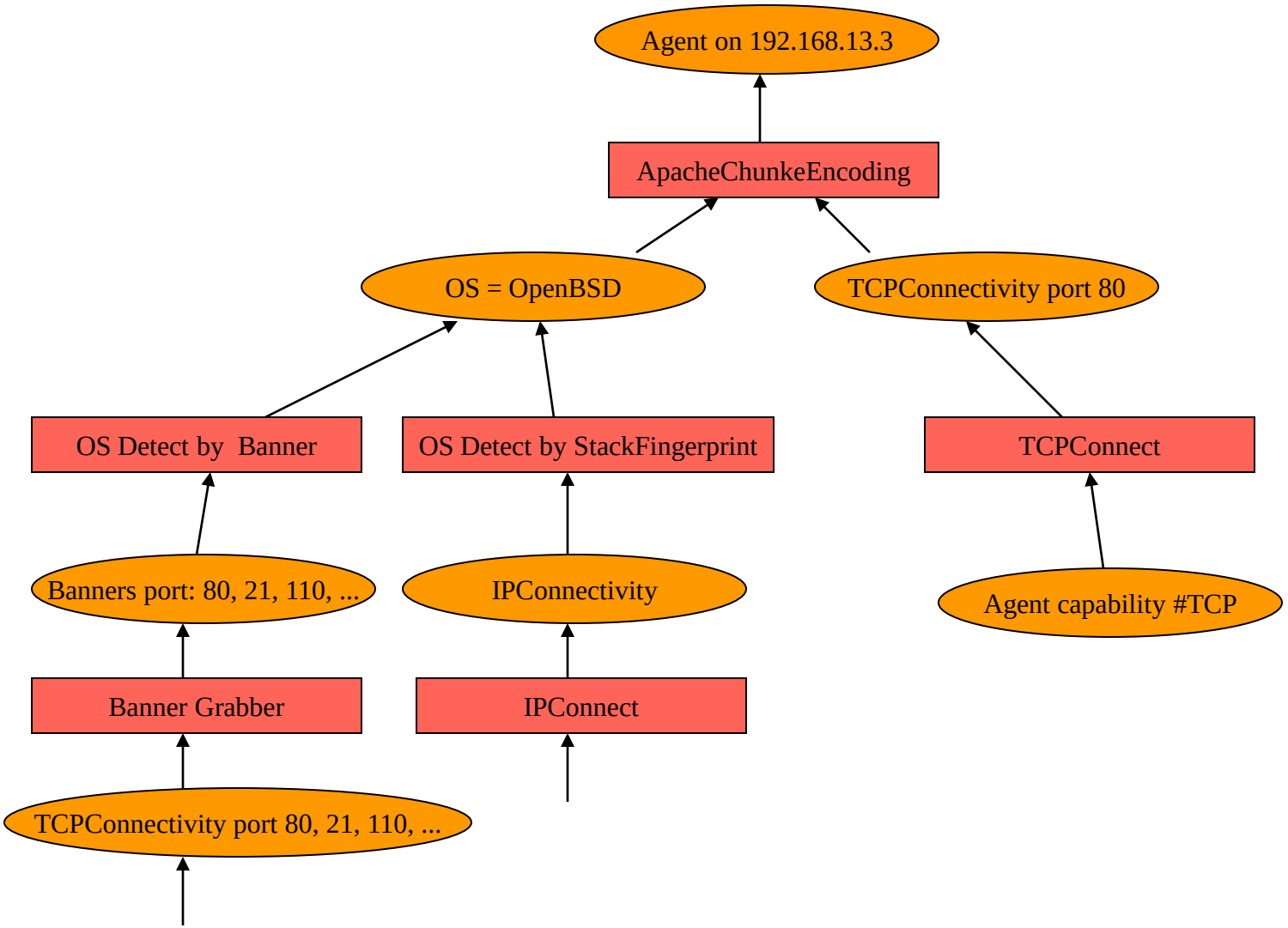
- Goals
  - Objectives of the attack
    - Obtain credit card numbers from the Database server
- Assets
  - Anything an attacker may need during the attack
    - OperatingSystemAsset, TCPConnectivityAsset and AgentAsset
- Actions
  - Atomic step that can be part of an attack
    - An exploit, a TCP connection and an OS identification method
- Agents: actors who can perform actions

# Attack Graph nodes

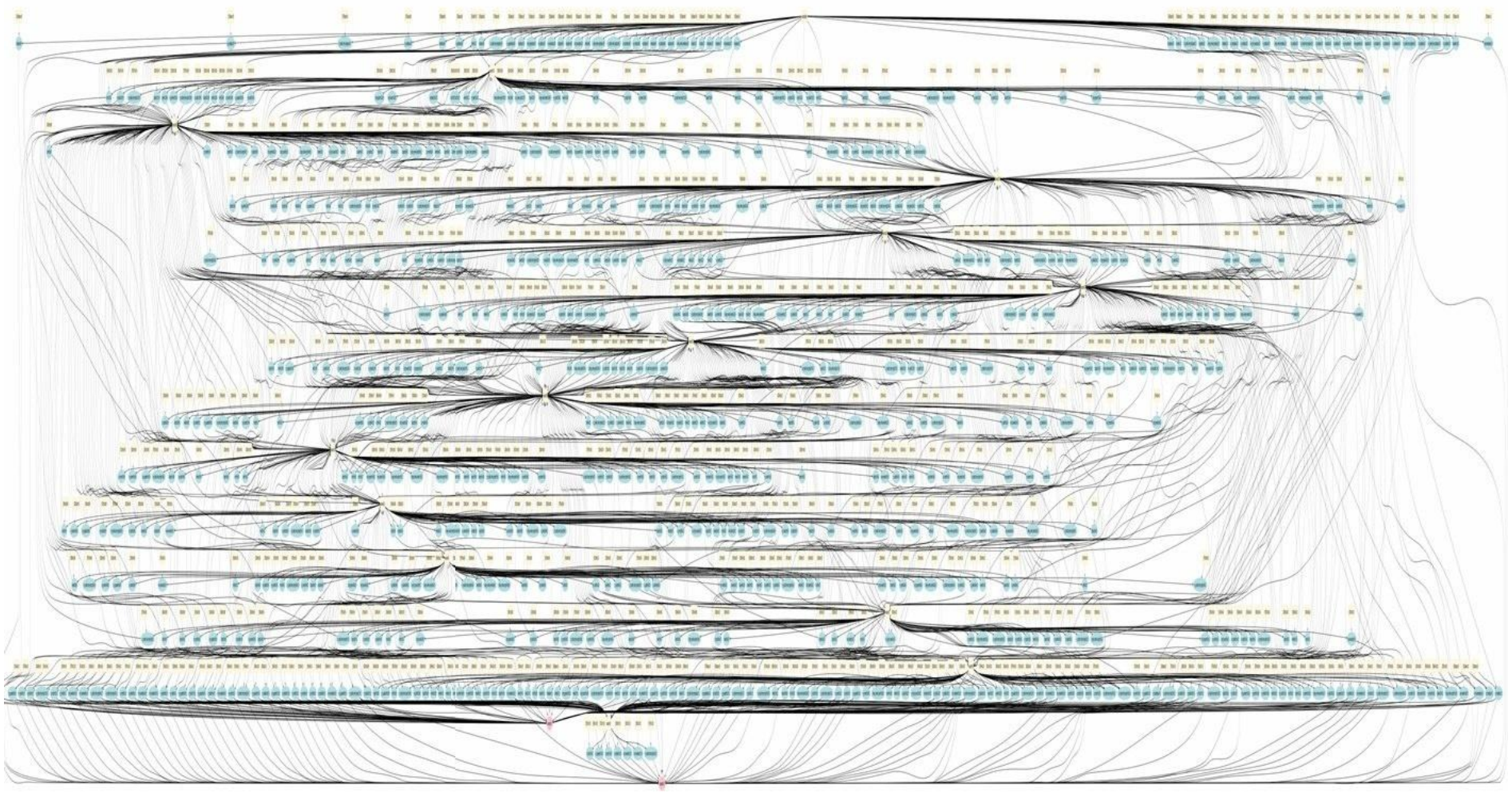
- The graph nodes are Actions and Assets

- Every action has an associated result
  - an Exploit gives as result an Agent on the target machine
- Actions have requirements (preconditions or subgoals)
  - Exploits are platform dependent and require knowledge of the Operating System of the target before execution
  - an HTTP Exploit requires an open port (and connectivity)

# Alternated layers of actions and assets



# An Attack Graph, a bit more real



From Noel – Jajodia: "Managing Attack Graph Complexity Through Visual Hierarchical Aggregation"

# Cost of actions

- Add realism and increase difficulty of planning problem
- Actions have an associated cost function
  - actions produce **noise**
    - network traffic
    - log lines
    - IDS events
  - expected **running time**
  - *planning: requires numerical effects*
- Actions have a **probability of success**
  - *requires probabilistic planning*

# Using PDDL planners
## from the International Planning Competition

# Search heuristics

- Don't construct the complete graph!

- Use an heuristic to explore the action space
- There are several variations of **A* search** to find good solutions
- A* search is based on exploring first the states $s$ that minimize

$$f(s) = g(s) + h(s)$$

  - where $g(s)$ is the cost of reaching state $s$
  - $h(s)$ is an estimation of the cost from $s$ to the goal.

# Relaxed problem

- $h(s)$ = estimated cost from $s$ to goal
- An acceptable heuristics must fulfill
  - $h(s) \leq$ real cost from $s$ to goal
- How do we compute $h(s)$?


- An interesting solution is to compute the cost of solving a relaxed version of the problem
  - ignore delete effects (e.g. crashing a machine)
  - consider only add effects

# PDDL experiments

- We have modeled the planning problem in the PDDL language
  - Planning Domain Definition Language
  - successor of the STRIPS language

- Language designed for the International Planning Competition
  - use the winning algorithms to generate plans
  - obtained good results with FF (Fast Forward) by Jörg Hoffmann

# Cost of the actions

- We consider a multidimensional cost of the actions:
  - execution time
  - noise / generated traffic
  - complexity of execution

- This improves the realism of the model, but also requires planning with numerical effects
  - new category in the planning competition
  - we have used Metric-FF by Jörg Hoffmann to solve domains with numerical effects

# Example of PDDL action

```
(:action MSRPC_DCOM_exploit
:parameters (?s - host ?t - host)

:precondition (and
    (compromised ?s)
    (TCP_connectivity ?s ?t port139)
    (has_application ?t MSRPC)
    (or (has_OS_version ?t WinNT) (has_OS_version ?t Win2000)
    (has_OS_version ?t Win2003) (has_OS_version ?t WinXP)) )

:effect (and
    (installed_agent ?t high_privileges)
    (increase (time) 32)
    (increase (noise) 210)
    (increase (uncertainty) 135) )
)
```

# Sample execution

- 3 networks with 40 hosts each
- 84 different actions
- resulting plan with 46 steps (pivoting 6 times)

```
instantiating 9673 easy, 794842 hard action templates
reachability analysis, yielding 2148 facts and 12973 actions
creating final representation with 2100 relevant facts
computing LNF
building connectivity graph
searching, evaluating 3189 states
63.29 seconds total time
```

# Fast algorithm for Probabilistic Planning

# Scenario 1: one goal, many exploits

- Attacker wants to gain access to the credit cards stored in database server *H*
- Attacker has a set of *n* remote exploits that he can launch against that server.

- The exploits result in the installation of a system agent when successful. The attacker
  - estimates probability of success based on the information already gathered
  - knows expected running time of each exploit

# How many exploits?

- Automation module of Core Impact
  - has 6 years of evolution

**Modules by category**

| Category | Modules |
|---|---|
| Remote Exploits | 177 |
| Local Exploits | 61 |
| Client-side Exploits | 140 |
| Denial-of-Service (DoS) Exploits | 27 |
| Utilities | 158 |
| **Total** | **563** |

**Target entry points**

| Operating System | Exploits | Unique Targets |
|---|---|---|
| Windows Vista | 42 | 116 |
| Windows 2003 | 113 | 743 |
| Windows XP | 216 | 1236 |
| Windows 2000 | 229 | 2403 |
| Windows NT | 19 | 84 |
| Linux | 155 | 478 |
| Solaris | 32 | 90 |
| AIX | 3 | 5 |
| Mac OS X | 9 | 53 |
| OpenBSD | 15 | 41 |
| FreeBSD | 7 | 17 |
| **Total** | **840** | **5266** |

- Deals with 840 exploits, targeting 5266 unique targets
- Tested on Class B networks with 512 hosts

# How to measure time and probability?

- Measure results of exploit executions in testing lab
  - 748 virtual machines in Core's testing lab
  - different OS and installed applications

- Get feedback from the users
  - anonymized feedback program in Impact
    - sensitive data is filtered out before sending it
  - natural option for Metasploit (in my opinion)

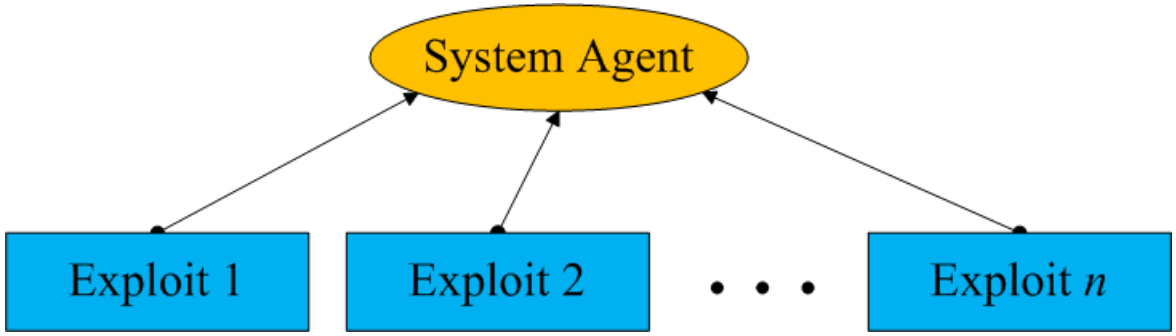
# Problem 1: one goal, many actions

- Let $T$ be a fixed goal
- Let $A_1, \ldots, A_n$ be a set of $n$ independent actions whose result is $T$.
  - each action $A_k$ has a probability of success $p_k$
  - and expected running time $t_k$
- Actions are executed until an action provides the goal $T$.

**Task:** Find the order of execution to minimize the expected total running time.

| | time | probability |
|---|---|---|
| action1 | 20 s | 0.55 |
| action2 | 30 s | 0.85 |
| action3 | 3 s | 0.02 |
| action4 | 120 s | 0.95 |

# Expected values




- If the actions are executed in the order $A_1, \ldots, A_n$
- The expected running time is:

$$T_{\{1\ldots n\}} = t_1 + \overline{p_1}\, t_2 + \ldots + \overline{p_1}\,\overline{p_2} \ldots \overline{p_{n-1}}\, t_n$$

- The probability of success is:

$$P_{\{1\ldots n\}} = p_1 + \overline{p_1}\, p_2 + \overline{p_1}\,\overline{p_2}\, p_3 + \ldots + \overline{p_1} \ldots \overline{p_{n-1}}\, p_n$$

# A nice Lemma

- Let $A_1$, …, $A_n$ be actions such that

$$\frac{t_1}{p_1} < \frac{t_2}{p_2} < \ldots < \frac{t_n}{p_n}$$

- Then

$$\frac{T_{\{1\ldots n-1\}}}{P_{\{1\ldots n-1\}}} < \frac{t_n}{p_n}$$

- Proof: by induction.

# Proposition 1 (solution)

- A solution to Problem 1 is to order the actions according to the coefficient $t_k / p_k$, and execute them in that order.

- The computational complexity of this solution is

$$O ( n \log n )$$

- In our small example:

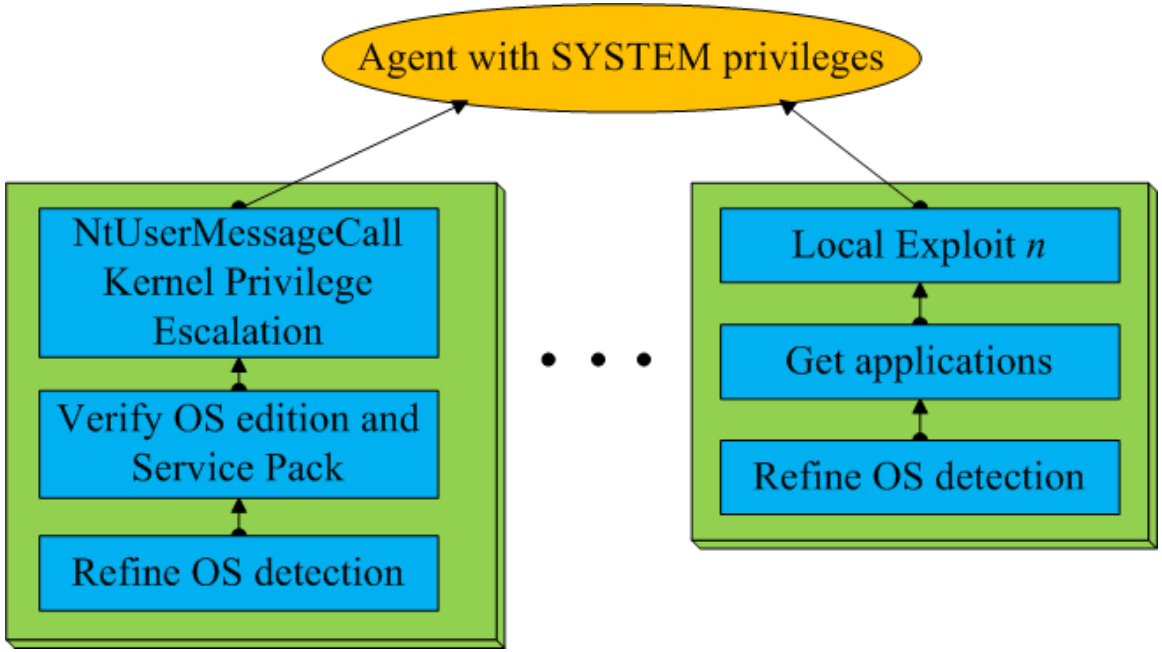
| | time | probability | coefficient | order |
|---|---|---|---|---|
| action1 | 20 s | 0.55 | 36.36 | 2 |
| action2 | 30 s | 0.85 | 35.29 | 1 |
| action3 | 3 s | 0.02 | 150.00 | 4 |
| action4 | 120 s | 0.95 | 126.31 | 3 |

# Problem 2: multiple strategies

- **strategy:** group of actions that must be executed in a specific order.
- The strategies are a way to incorporate the expert knowledge of the attacker in the planning system
- Cf. the opening moves in chess or Go

# Strategy example

- Example: the attacker has an agent with low privileges on host *H* and his goal is to obtain system privileges



# Problem 2: one goal, many strategies

- Let $T$ be a fixed goal, and let $G_1, \ldots, G_n$ be a set of $n$ strategies.
- Each strategy $G_k$ is composed by a **group of ordered actions**.
- If all the actions in a group are successful, the strategy fulfills the goal $T$.

- **Task:** Minimize the expected total running time.

# Proposition 2 (solution)

- Calculate expected running time of each group

$$T_G = t_1 + p_1\, t_2 + p_1\, p_2\, t_3 + \ldots + p_1\, p_2 \ldots p_{n-1}\, t_n$$

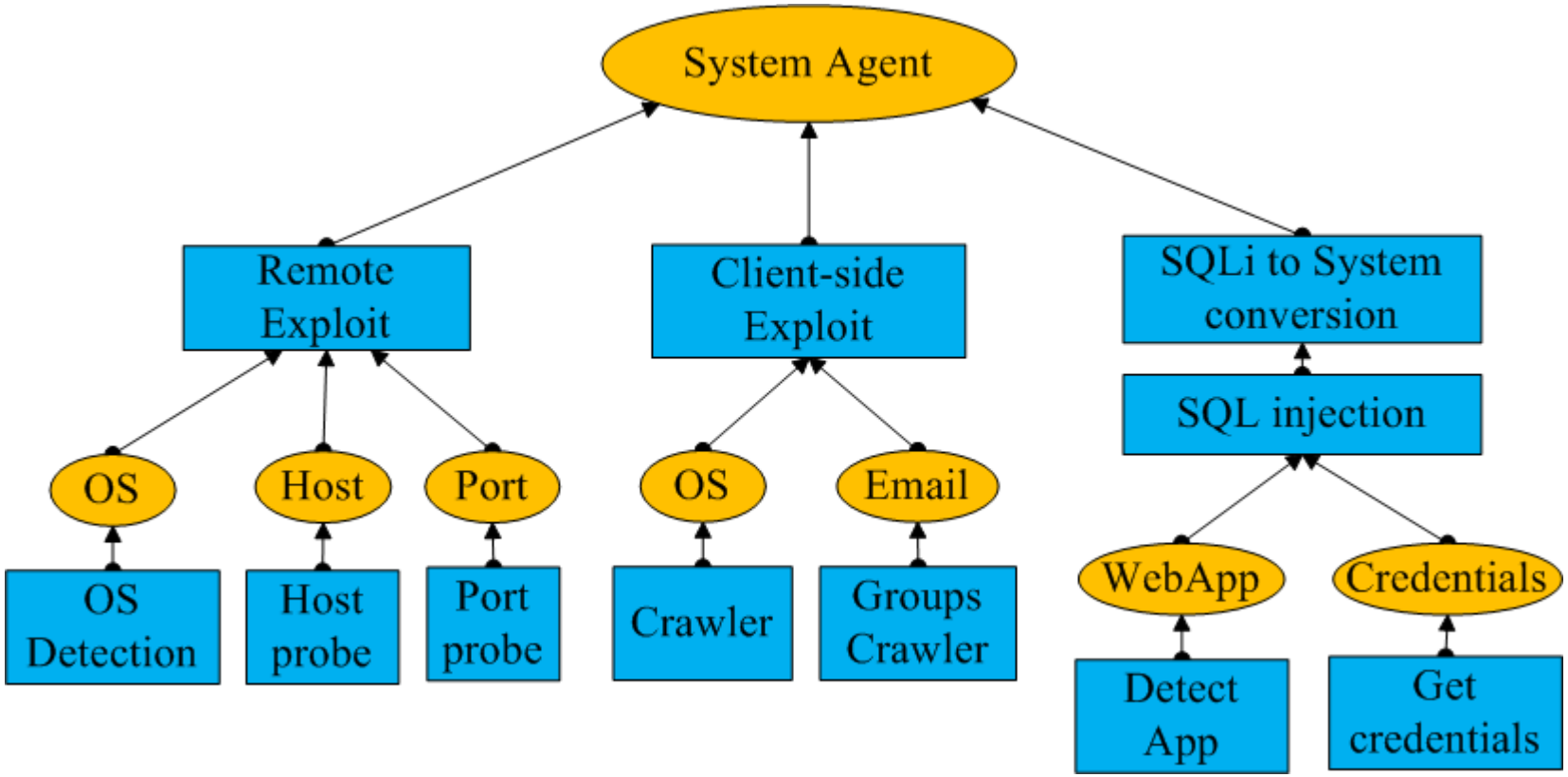
- Calculate probability of success

$$P_G = p_1\, p_2 \ldots p_n$$

- Sort the strategies according to $T_G$ / $P_G$
- In each group execute the actions until an action fails
  - this is the technical part of the demonstration

# Problem 3: two layers attack tree

- Groups of actions bounded by an **AND relation**
  - the order of actions is **not** specified
  - in previous problem the order was fixed



# Proposition 3 (solution)

- How to order the actions in each group?

- **Lemma:** To minimize the expected total running time, the actions must be ordered according to the coefficient

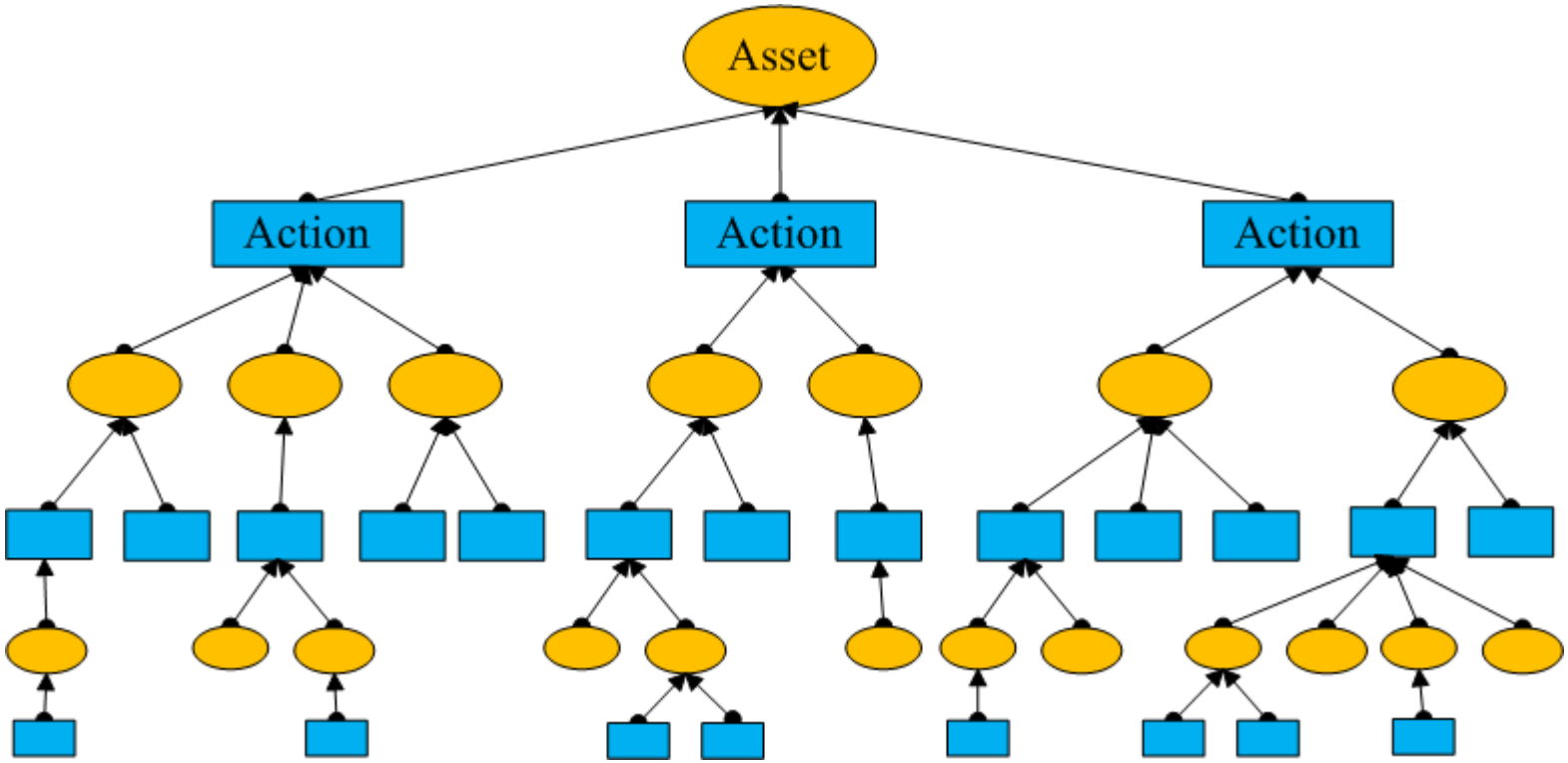
$$t_k / (1 - p_k)$$

- **Intuition:** the actions that have higher probability of failure have higher priority, since a failure ends the execution of the group.

# Dynamic Replanning

# Problem 4: attack tree

- Attack tree, alternating Assets and Actions



# Proposition 4 (solution)

- Compose all previous algorithms
- **AND group:** can be considered as a single node with probability $P_G$ and execution time $T_G$
- **OR group:** the node that minimizes the $t/p$ coefficient will be executed first
  - considered as the cost of the group in a single step plan.
- By iteratively reducing groups of nodes, we build a single path of execution

# Dynamic replanning

- After executing a step of the plan, the costs may be modified and the shape of the graph may vary.

- This is where dynamic replanning comes in.
  - Since the planning algorithm is very efficient, we can replan after each execution
  - and build a new path of execution.

# Conclusion

# Summary

- Attack planning – from the attacker's point of view
  - consider all the steps of an attack, not only exploits
  - model the attacker's knowledge of the world
- Extension to classic Attack Graphs
  - numerical effects
    - expected running time
  - probabilistic effects
    - probability of success
- Fast algorithm for Probabilistic Attack Planning
  - works in a relevant part of real-world scenarios
  - demonstrations that the solution is optimal in specified scenarios

# New research direction

- During the last years, the difficulties in our research were related to the exponential nature of planning algorithms
  - especially in the probabilistic setting
- Our efforts were directed toward the aggregation of nodes and simplification of the graphs
  - to tame the size and complexity of the problem
- Having a very efficient algorithm in our toolbox gives us a new direction of research:
  - refine the model
  - break down the actions into smaller parts
  - without fear of producing an unsolvable problem.

# Finer analysis of exploits

- A future step: divide the exploits into basic components.
- This decomposition gives a better probability distribution of the exploit execution
- Example: Debian OpenSSL Predictable Random Number Generation Exploit
  - brute forces the 32,767 possible keys.
  - each iteration is considered as a basic action
  - some keys are more probable than others
- Finer level of control over the exploit execution
  - produces gains in the total execution time


# Thank you!

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