Attack and Defense Modeling with BDMP (Boolean logic Driven Markov Processes)

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EDF R&D

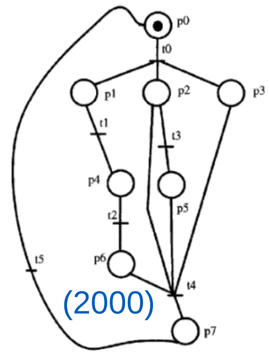
LEADING THE ENERGY CHANGE

Agenda

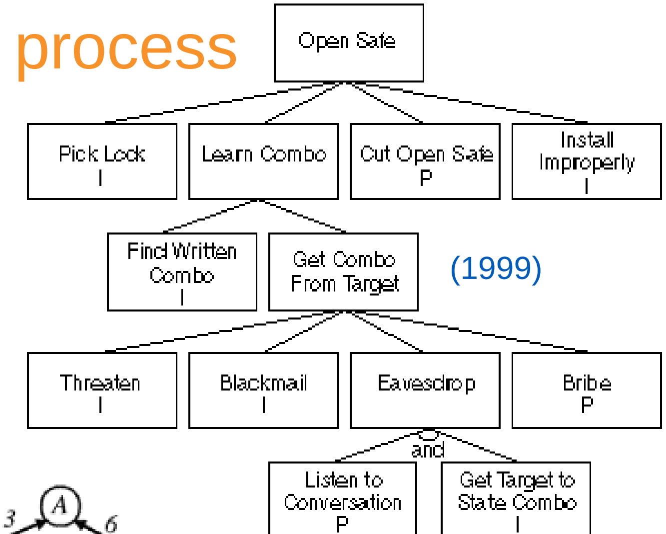
- **Introduction**
  - Graphical attack modeling
- **Attack modeling with BDMP**
  - Formalism description
  - Example & quantifications
- **Defensive aspects modeling**
  - Augmented theoretical framework
  - Use-case & quantifications
- **On-going work, perspectives**
  - Recent advance, future work
- **Conclusion and Q&A**

Graphical modeling of computer attacks

- Graphical representation of an attack process
  - Formalize reasoning
  - Share standpoints
  - Enhance coverage

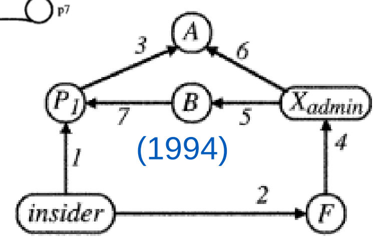


(2000)

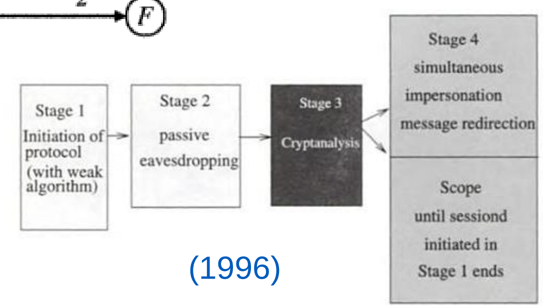


(1999)

- An active field of research
  - Static models (eg. attack tree)
  - Dynamic models (eg. Petri-net)



(1994)

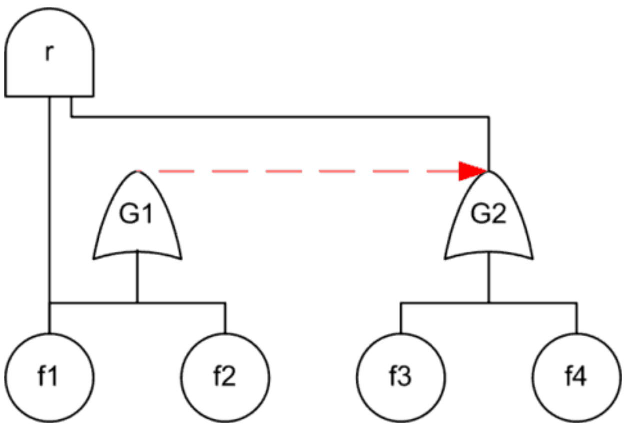


(1996)

- Different trade-offs
  - Readability, scalability, modeling and quantification capabilities

BDMP, the potential for an attractive trade-off

- Interest proven in reliability and safety engineering

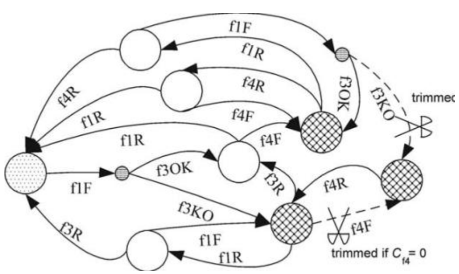


✓ Dynamic

✓ Readable

✓ Tractable

A new formalism that combines advantages of fault-trees and Markov models: Boolean logic Driven Markov Processes
Reliability Engineering and System Safety, Vol. 82, Issue 2, Nov. 2003, pp.149-163



- Invented and used at EDF (NPP safety, substations, data centers reliability,…)
- Complete theory and software framework

⇒ Adaptation to attack modeling

BDMP - Application to attack modeling

Main ideas

- New semantics to the graphical representation of attack trees
- Markov processes are associated to the leaves (actions/events)
  - Two modes, “Active” and “Idle”
  - Mode of a leaf = f (states of some selected other leaves)
- Dynamic, model attack sequences

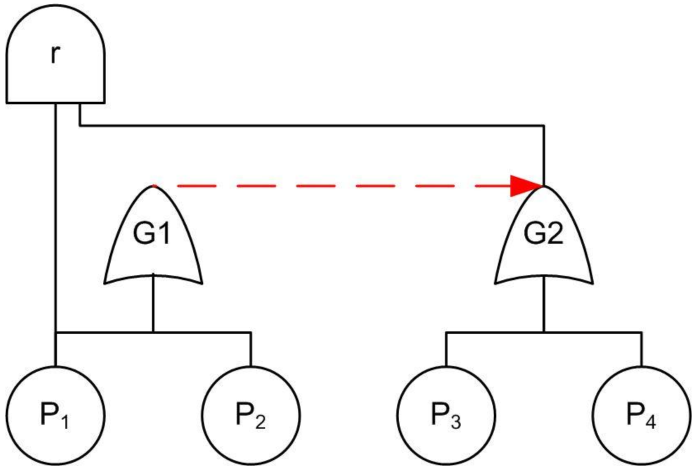
Graphical elements

- BDMP = $\{\mathcal{A}, r, T, \{P_i\}\}$

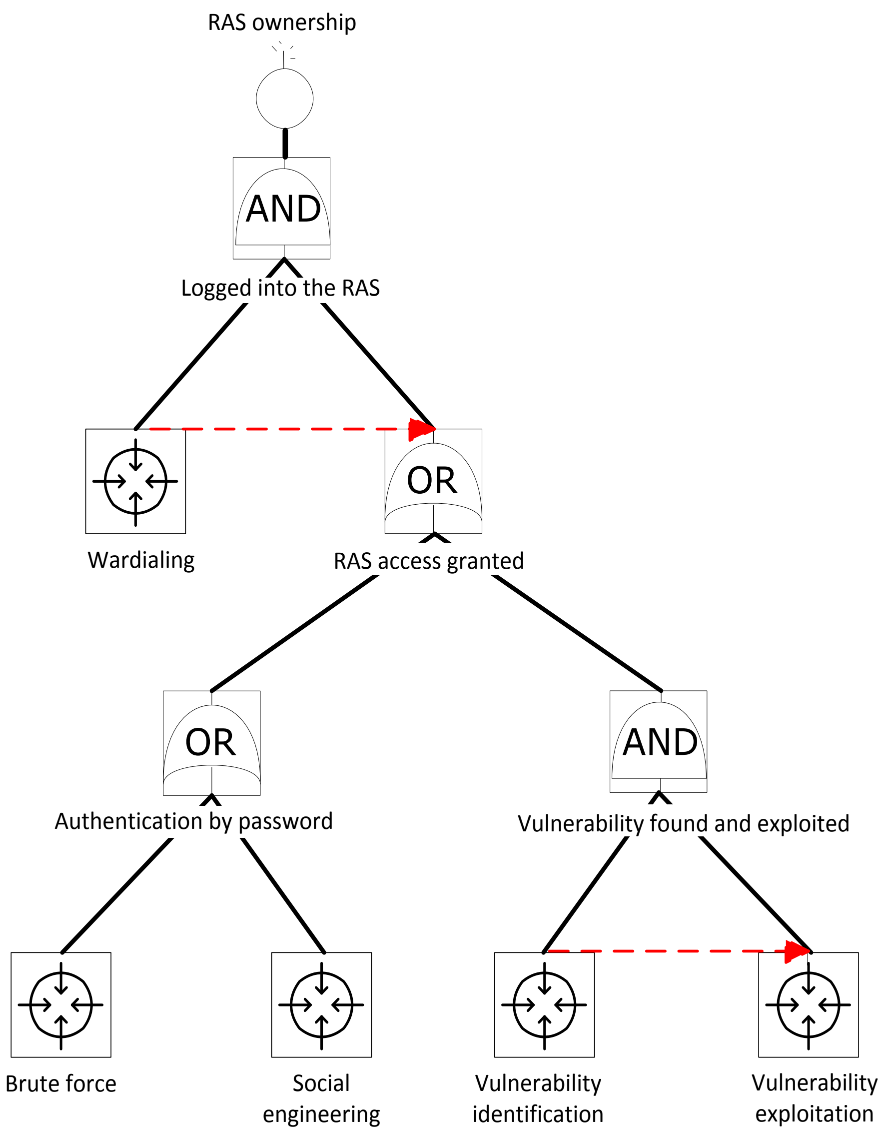
$\mathcal{A}$ = Attack Tree, r = top event,

G1 = secondary top, T = trigger,

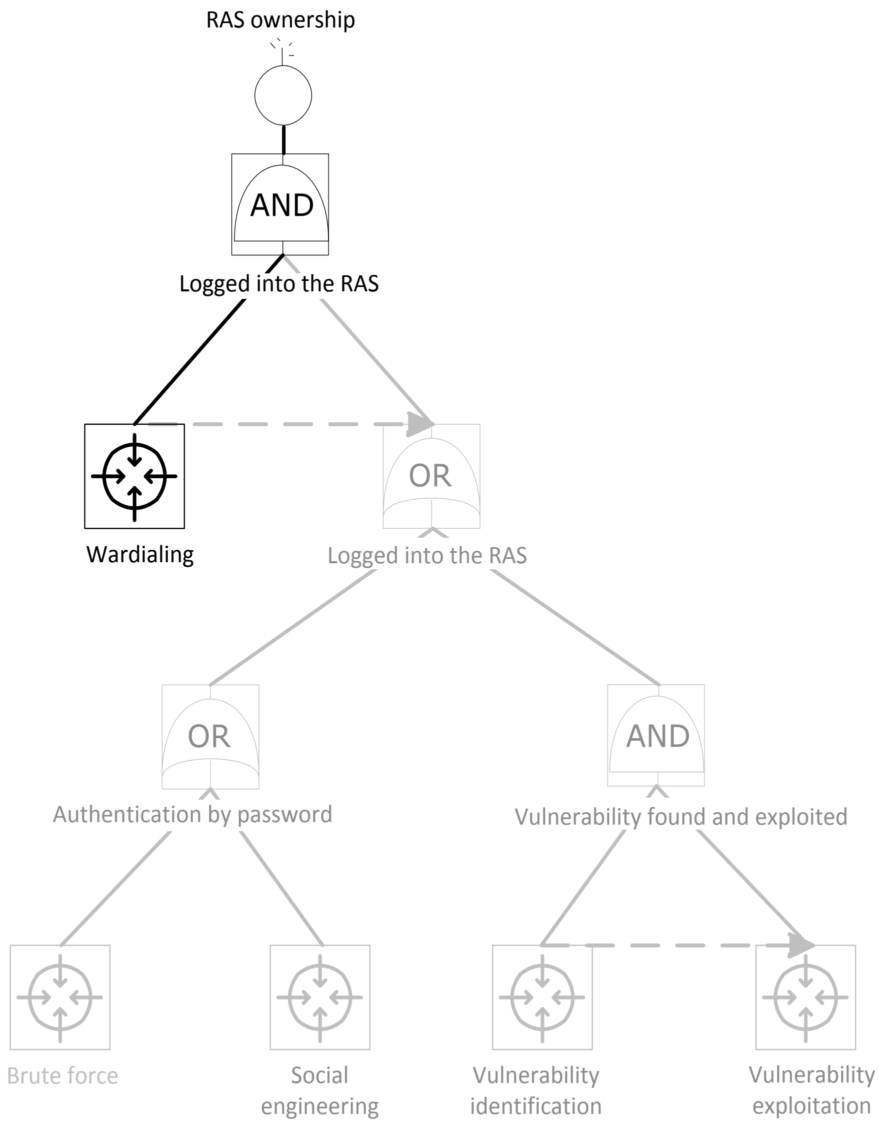
P_i =“triggered” Markov processes



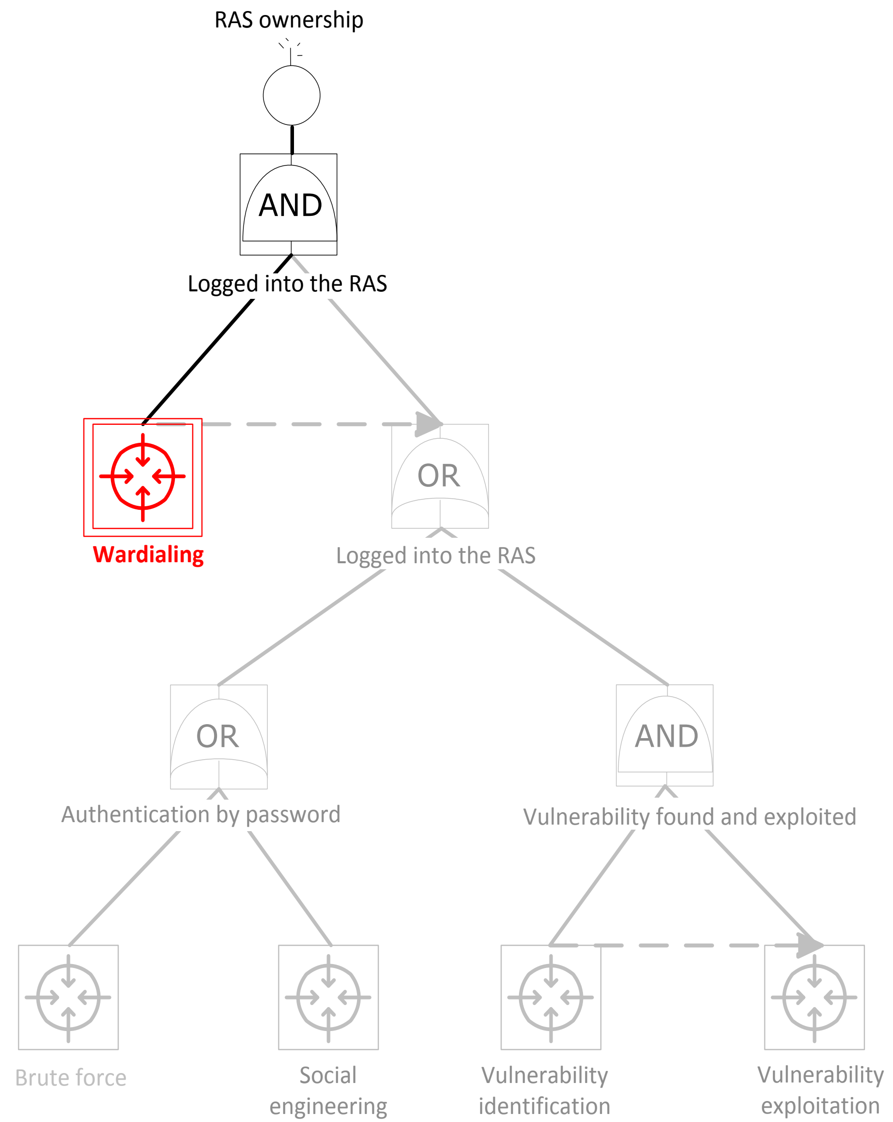
A first feel: a simple Remote Access Server attack



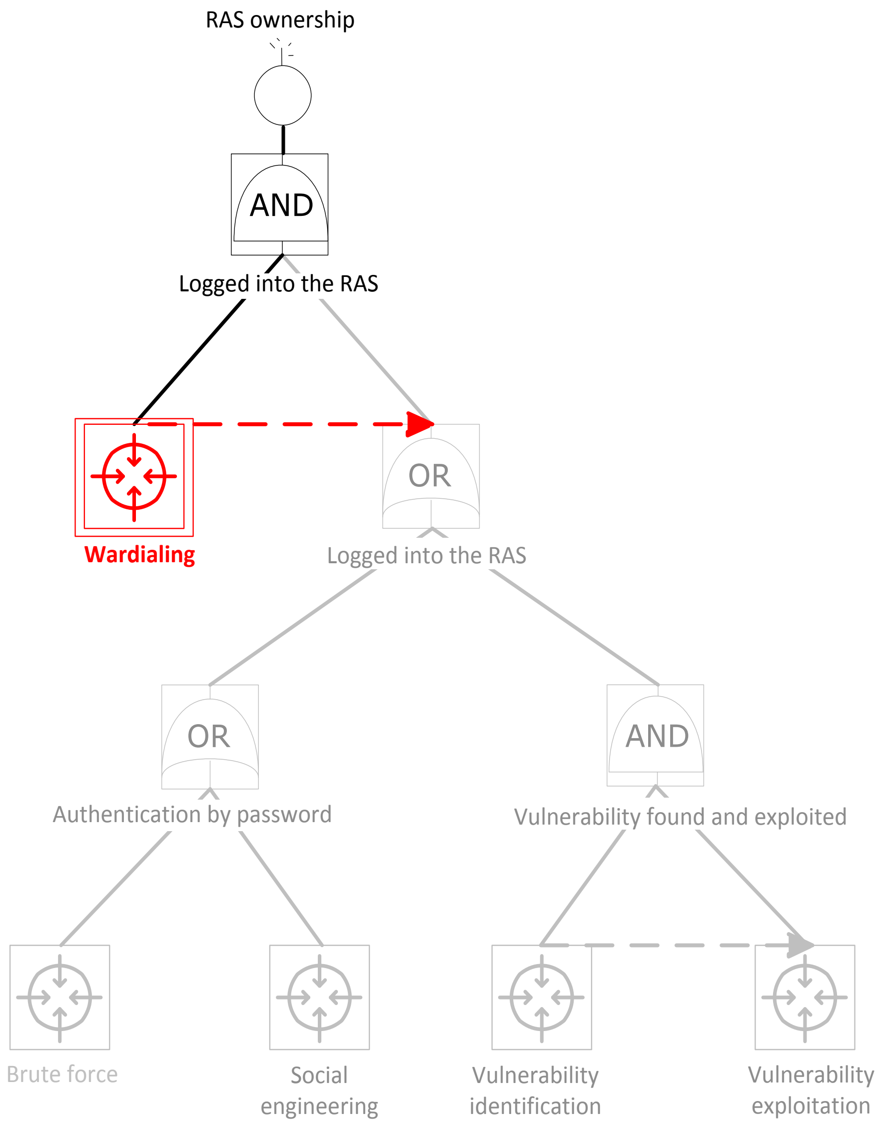
RAS attack BDMP – Step 0 (attack just started)



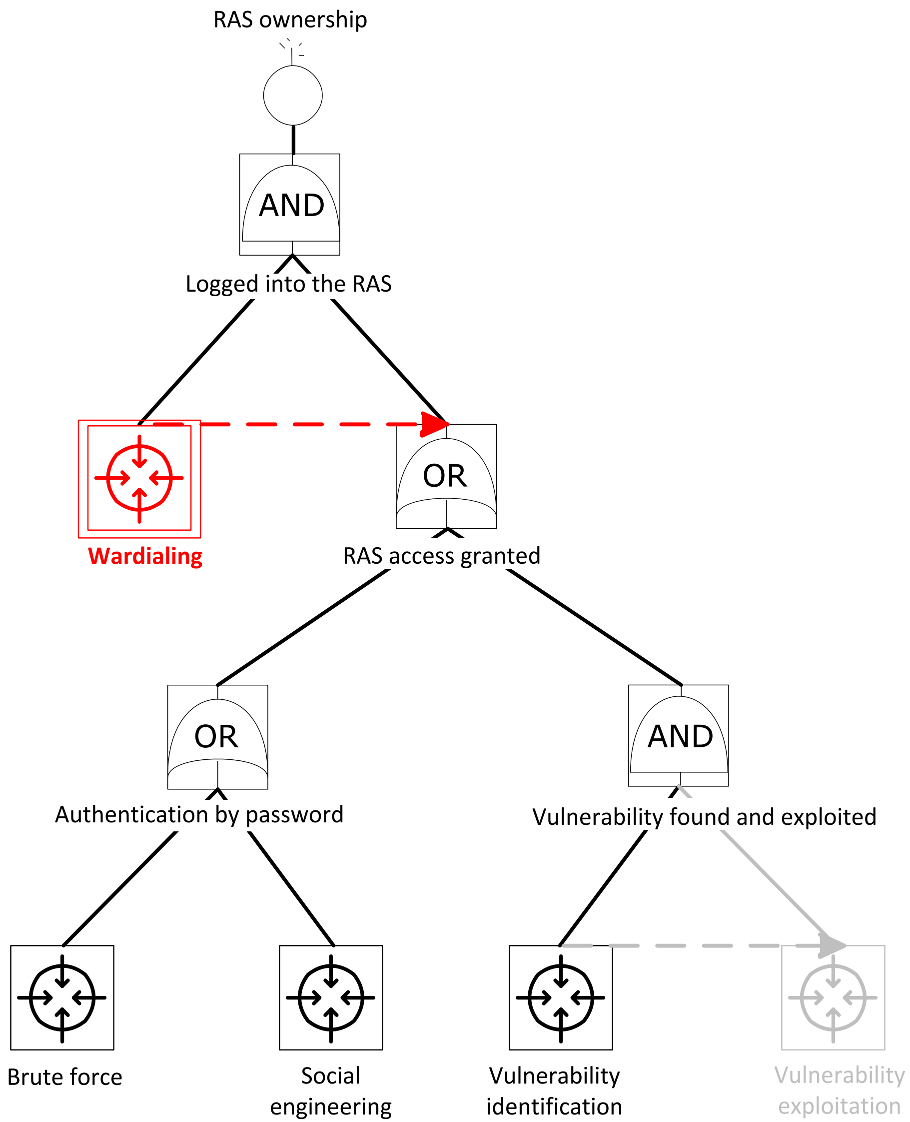
RAS attack BDMP – Step 1



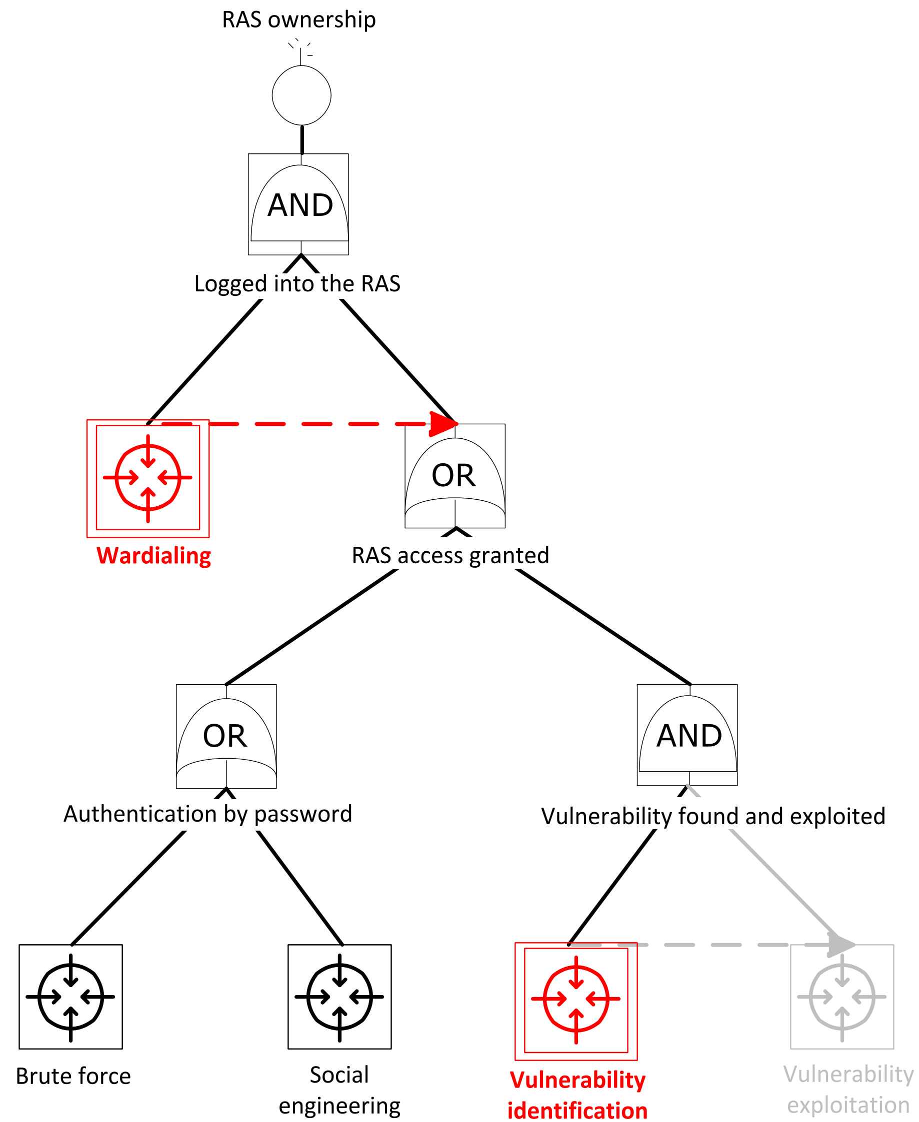
RAS attack BDMP – Step 1



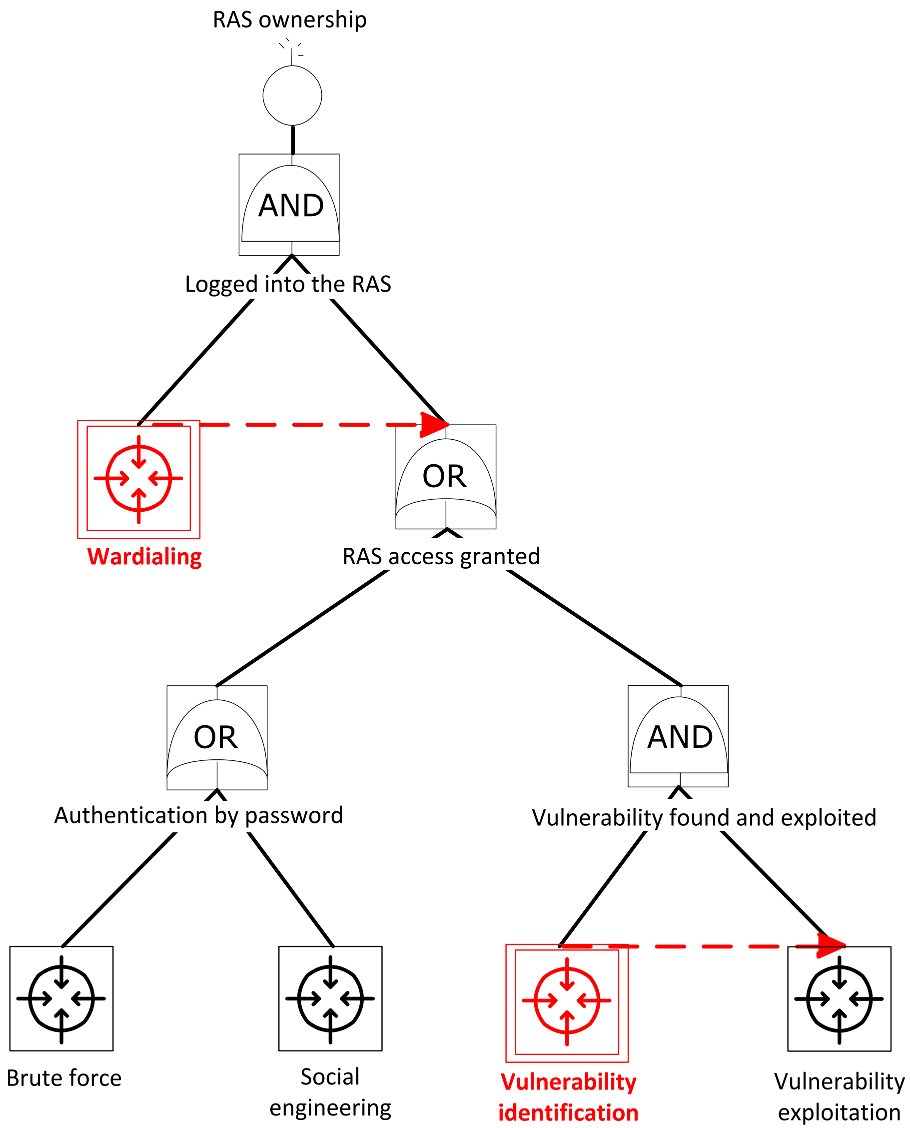
RAS attack BDMP – Step 1



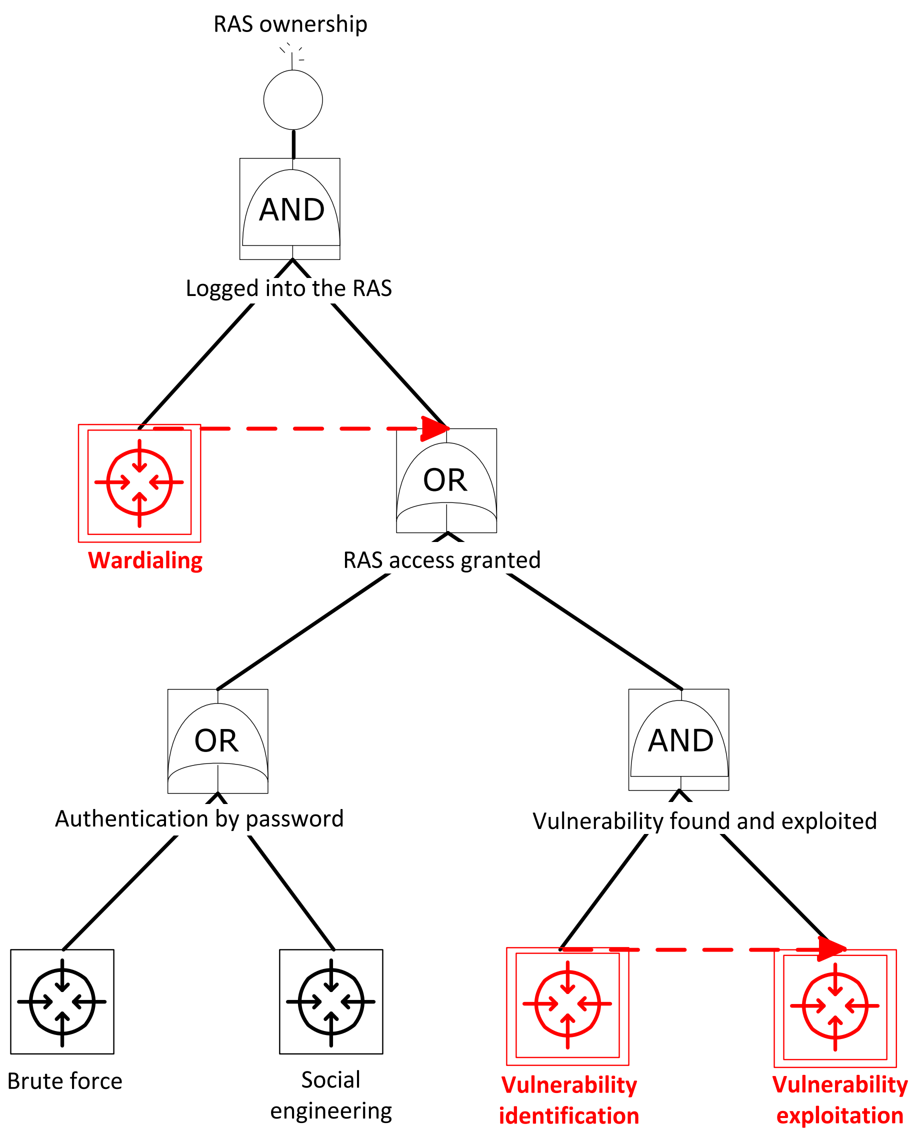
RAS attack BDMP – Step 2



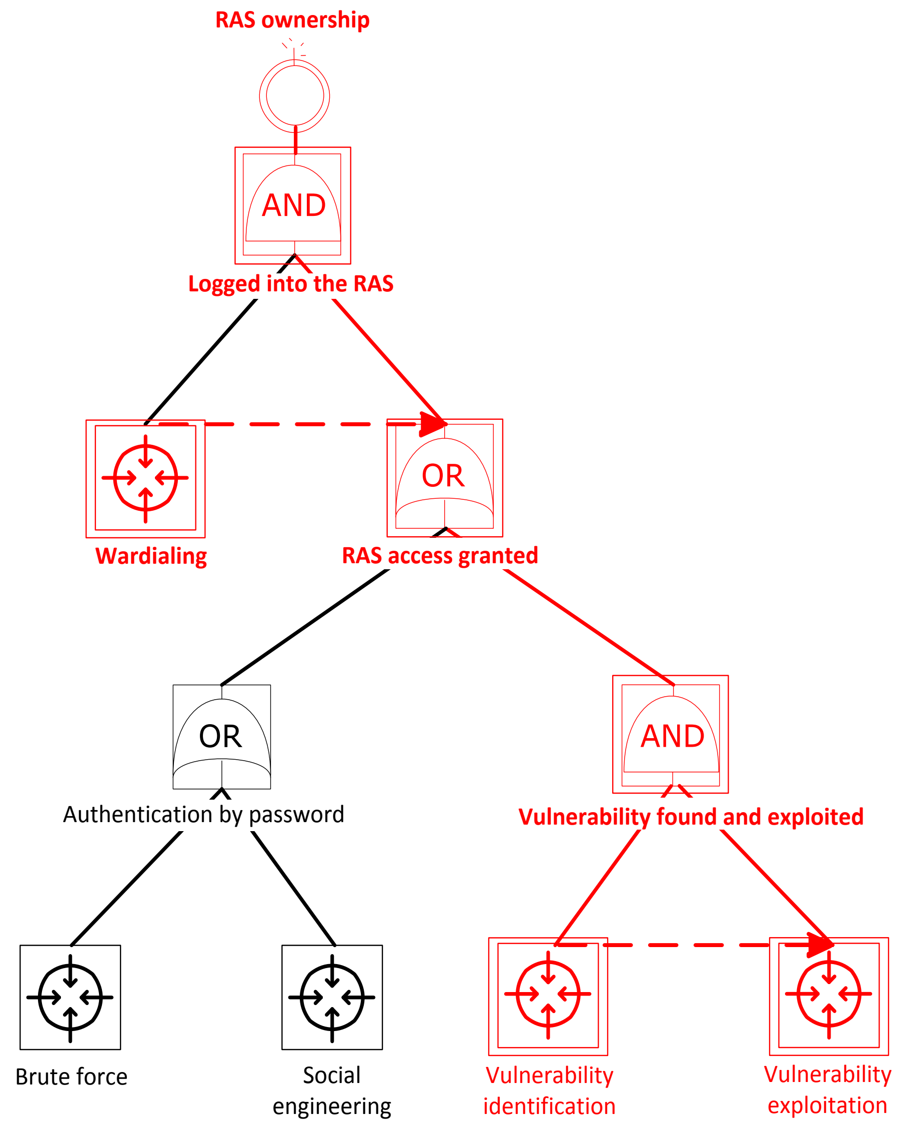
RAS attack BDMP – Step 2



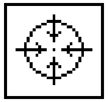
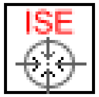
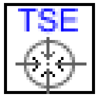
RAS attack BDMP – Step 3



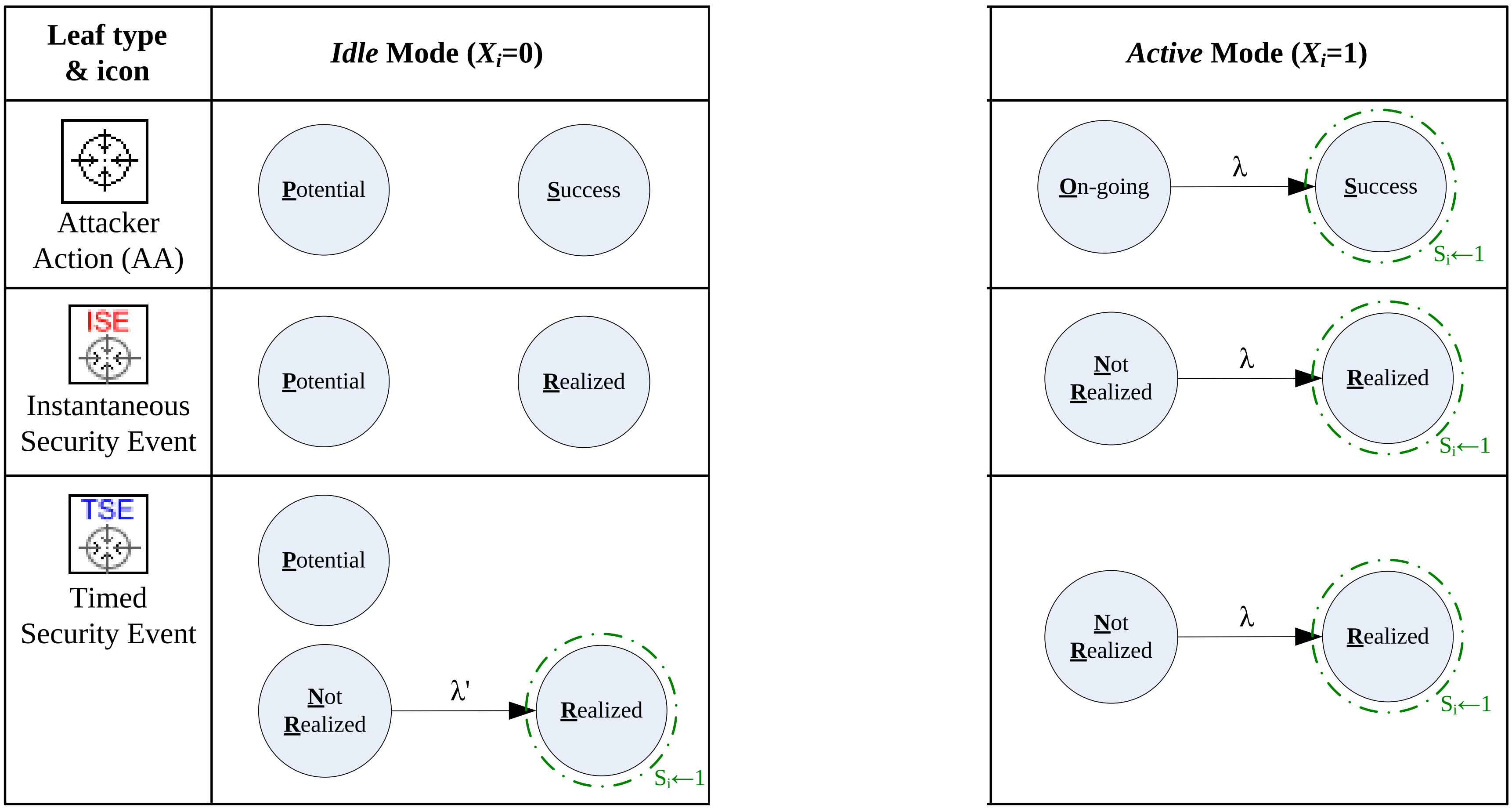
RAS attack BDMP – Attacker’s objective reached



A zoom on the three basic security leaves

Leaf type & icon
 Attacker Action (AA)
 Instantaneous Security Event
 Timed Security Event

A zoom on the three basic security leaves



A zoom on the three basic security leaves

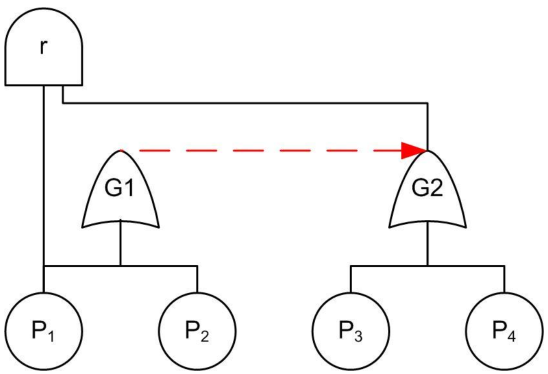
Leaf type & icon	*Idle* Mode (X_i=0)	Transfer between modes	*Active* Mode (X_i=1)
Attacker Action (AA)	**P**otential; **S**uccess	P⇔O (with $Pr = 1$) S⇔S (with $Pr = 1$)	**O**n-going →λ→ **S**uccess ($S_i \leftarrow 1$)
ISE Instantaneous Security Event	**P**otential; **R**ealized	P⇨NR (with $Pr=1-\gamma$) P⇨R (with $Pr = \gamma$) R⇔R (with $Pr = 1$) P⇦NR (with $Pr = 1$)	**N**ot **R**ealized →λ→ **R**ealized ($S_i \leftarrow 1$)
TSE Timed Security Event	**P**otential; **N**ot **R**ealized →λ'→ **R**ealized ($S_i \leftarrow 1$)	P⇨NR (with $Pr = 1$) NR⇔NR (with $Pr=1$) R⇔R (with $Pr = 1$)	**N**ot **R**ealized →λ→ **R**ealized ($S_i \leftarrow 1$)

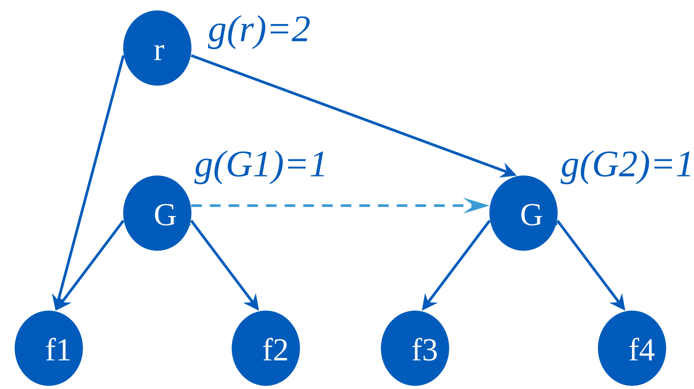
EDF

Formal foundations – snapshot 1/3

A (security-oriented) BDMP $(\mathcal{A}, r, T, \{P_i\})$ is made of

- An attack tree $\mathcal{A} = \{E, L, g\}$
  - a set $E = G \cup B$, where G is a set of gates and B a set of basic events
  - (E, L) a directed acyclic graph, with L a set of oriented edges (i, j)
  - a function g, defining the gates ($g{:}G \rightarrow N^*$, with $g(i)$ the gate parameter k)





- A main top objective r
- Set of triggers T is a subset of $(E - \{r\})x(E - \{r\})$ such that

$$\forall (i, j) \in T,\ i \neq j \ and \ \forall (i, j) \in T, \forall (k,l) \in T, i \neq k \Rightarrow j \neq l$$

Formal foundations – snapshot 2/3

- $P = \{P_i\}_{i \in E}$, triggered Markov Processes $\{Z_0^i(t), Z_1^i(t), f_{0\to1}^i, f_{1\to0}^i\}$
  - $Z_0^i(t)$ and $Z_1^i(t)$ two homogeneous Markov process
  - $f_{0\to1}^i(x)$ and $f_{1\to0}^i(x)$ two “probability transfer functions”
    - For k in $\{0, 1\}$ (modes), A_k^i state-space of $Z_k^i(t)$
    - $S_k^i \subset A_k^i$, subset that generally corresponds to attacker action successes states (or event realization states)
    - For any $x \in A_0^i$, $f_{0\to1}^i(x)$ is a probability distribution on A_1^i such that if $x \in S_0^i$, then $\sum_{j \in S_1^i} (f_{0\to1}^i(x))(j) = 1$
    - For any $x \in A_1^i$, $f_{1\to0}^i(x)$ is a probability distribution on A_0^i such that if $x \in S_1^i$, then $\sum_{j \in S_0^i} (f_{1\to0}^i(x))(j) = 1$

Formal foundations – snapshot 3/3

- Three families of Boolean functions of the time
  - Structure functions $(S_i)_{i \in E}$

$$\forall i \in G,\ S_i \equiv \sum_{j \in sons(i)} S_j \geq g(i)$$

$$\forall j \in B,\ S_j \equiv Z^j_{X_j} \in S^j_{X_j}$$, with $X_j = 0$ or 1, indicating the mode in which P_j is at time t

  - Process selectors $(X_i)_{i \in E}$

If i is a root of $\mathcal{A}$, then $X_i = 1$ else

$$X_i \equiv \neg\left[\left(\forall x \in E, (x,i) \in L \Rightarrow X_x = 0\right) \vee \left(\exists x \in E / (x,i) \in T \wedge S_x = 0\right)\right]$$

  - Relevance indicators $(Y_i)_{i \in E}$

If $i = r$ (finale objective), then $X_i = 1$ else

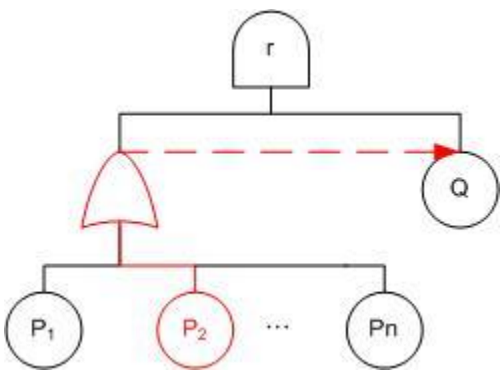
$$Y_i \equiv \left(\exists x \in E / (x,i) \in L \wedge Y_x \wedge S_x = 0\right) \vee \left(\exists y \in E / (i,y) \in T \wedge S_y = 0\right)$$

Mathematical properties

Robustness

- Theorem 1: $(S_i)(X_i)(Y_i)_{i \in E}$ are computable whatever the BDMP structure
- Theorem 2 : Any BDMP, defined at time t by the modes and the P_i states, is a valid homogeneous Markov process

Combinatory reduction by “relevant event filtering”



- After attack step P_2, all the others P_i are not relevant anymore: nothing is changed for “r” if we inhibit them
- The number of sequences leading to the top objective is
  - n, if we filter the relevant events $(\{P_1,Q\},\{P_2,Q\},\ldots)$
  - exponential otherwise $(\{P_1,Q\},\{P_1,P_2,Q\}, \{P_1,P_3,Q\},\ldots)$

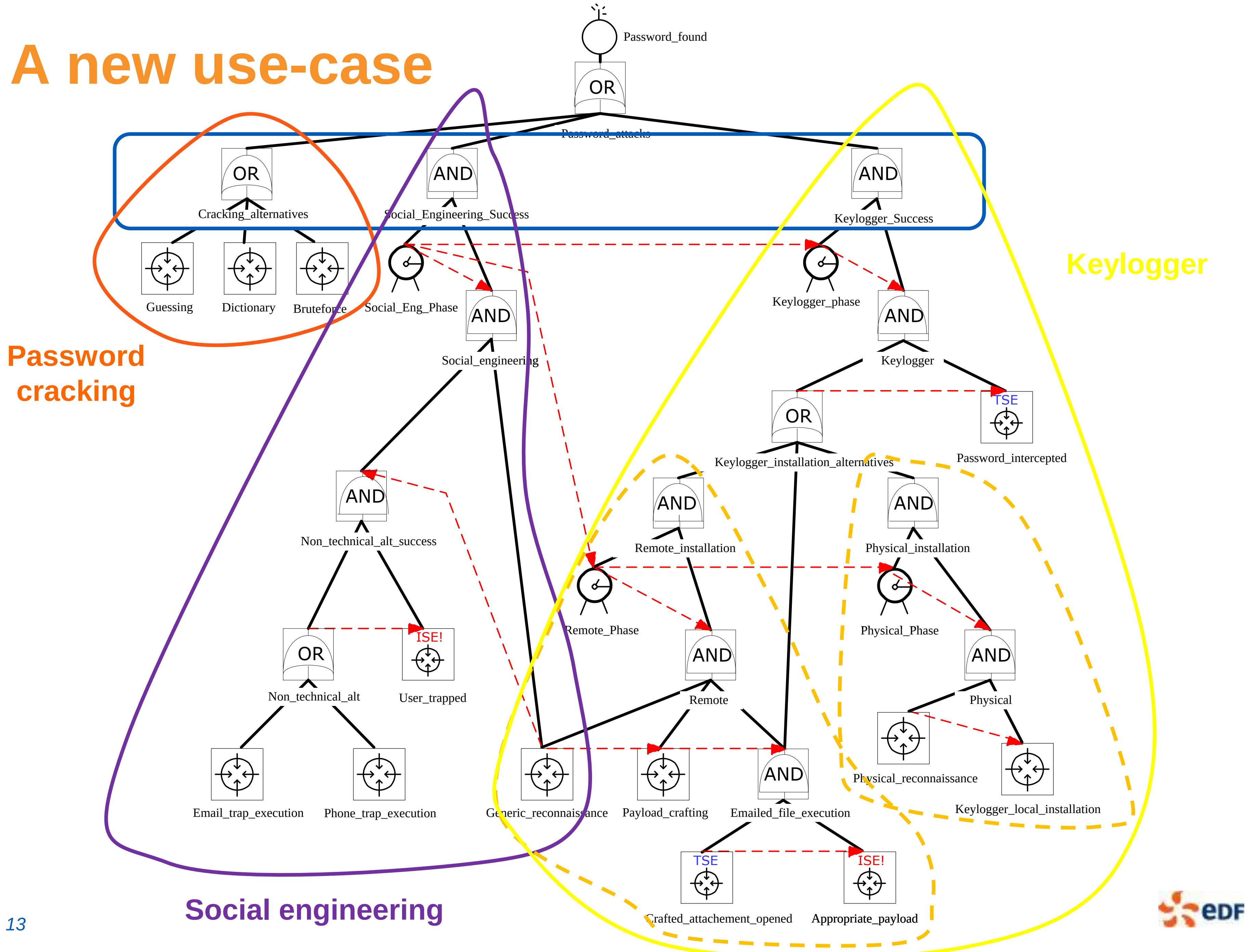
- Theorem 3: if the P_i are such that $\forall i \in B, \forall t, \forall t' \geq t, S_i(t) = 1 \Rightarrow S_i(t') = 1$ *
$Pr(S_r(t)=1)$ is unchanged whether irrelevant event ($Y_i=0$) are trimmed or not

* This is always the case in our framework (~ non-repairable in reliability studies)

Quantifications

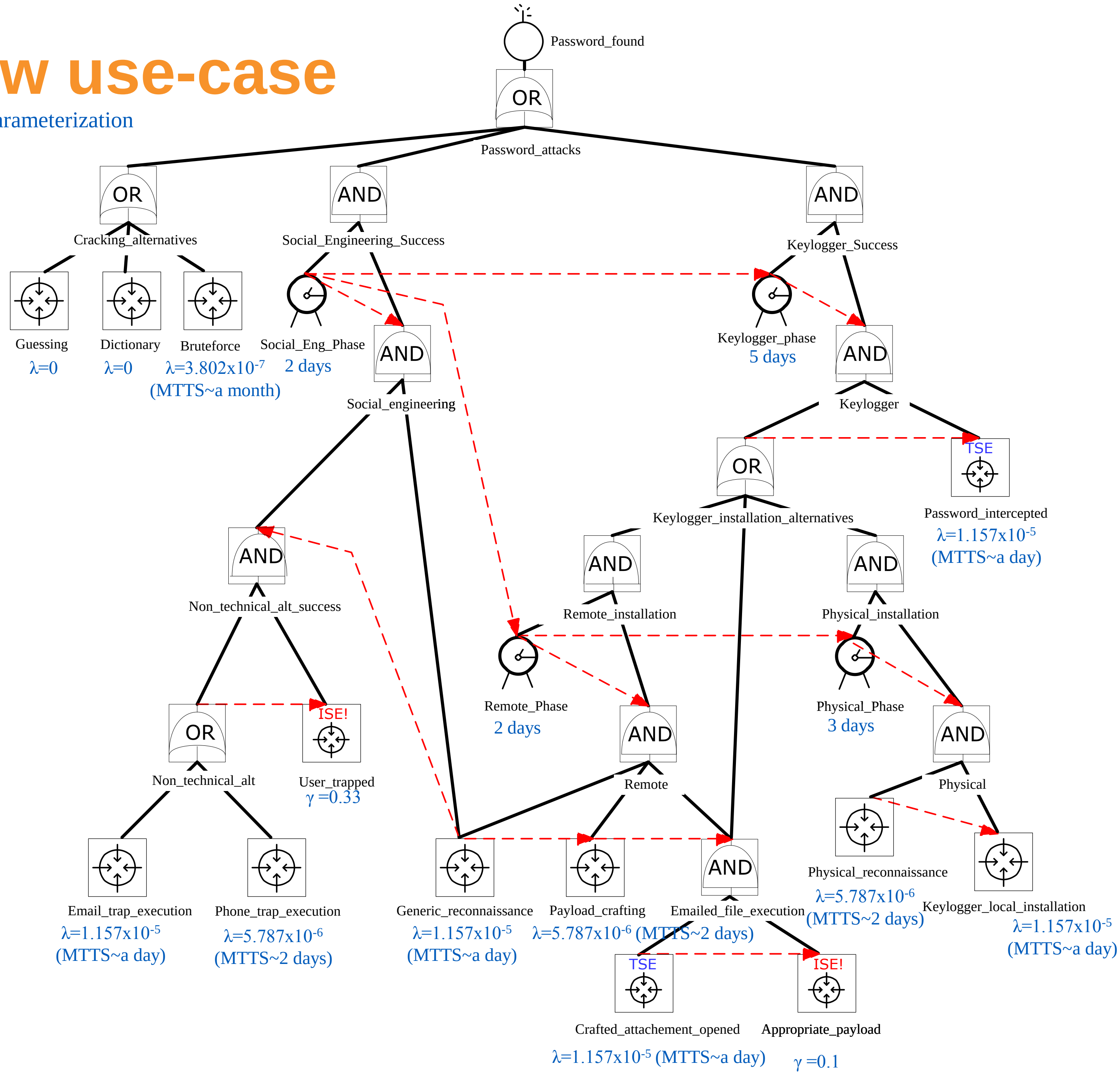
- Time-domain analysis – Leveraging the BDMP framework
  - Quantification tools, algorithms and optimizations
  - Efficient sequence exploration with trimming
    - Probability to reach the objective in a given time
    - Overall mean time to the attack success
    - Probability of each explored sequence
    - Ordered list of sequences
- Time-independent (static) - Classical attack tree parameters
  - Monetary cost → scenario cost, average attack cost
  - Boolean indicators (specific requirements, properties)
  - Minimum attacker skills

A new use-case



A new use-case

Example of parameterization



Results

- Overall probability in a week = 0.422
- Overall MTTS = 22 days
- Ordered list of attack sequences (654 sequences)

	Sequences	Probability in a week	Average duration	Contrib.
1	<Social Eng>Generic reconn., Email trap exec., User trapped	1.059×10^{-1}	9.889×10^{4}	25.1%
2	<Social Eng>Generic reconn., Phone trap exec., User trapped	5.295×10^{-2}	9.889×10^{4}	12.5%
3	Bruteforce	2.144×10^{-2}	5.638×10^{4}	5.1%
4	<Social Eng></Social Eng><Keylogger><Remote></Remote> <Physical> Physical reconn., Keylogger local installation, Password intercepted	1.749×10^{-2}	2.976×10^{5}	4.1%
5	<Social Eng></Social Eng><Keylogger> <Remote>*Generic reconnaissance* </Remote><Physical>Physical reconnaissance, Keylogger local installation, Password intercepted	1.350×10^{-2}	3.677×10^{5}	3.2%
6	<Social Eng>*Generic reconnaissance*, *Email trap execution*, *User trapped(failure)*, Bruteforce	1.259×10^{-2}	2.610×10^{5}	3.0%
...				
20	<Social Eng></Social Eng><Keylogger><Remote>Generic reconnaissance, Payload crafting, Appropriate payload, Password intercepted	2.500×10^{-3}	2.761×10^{5}	0.6%
...				
34	<Social Eng></Social Eng><Keylogger> <Remote>Generic reconn., *Payload crafting* </Remote> <Physical>*Crafted attachement opened*, *Appropriate payload*, Physical reconn., Keylogger local installation, Password intercepted	1.506×10^{-3}	4.594×10^{5}	0.4%

Detection Modeling

Main points

- The IOFA distinction: **I**nitial / **O**n-going / **F**inal / **A** posteriori
- Changes in the parameters and/or in the BDMP structure
- Introduction of a “Detection status indicator” D_i

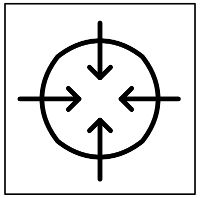
Changes in the modes

- “Active” is divided in “Active Undetected” and “Active Detected”
- Allows for parameter change, and even leaf cancellation
- The mode is selected based on $X_i D_i$

$X_i D_i$	00	01	10	11
Mode	Idle (I)		Active Undetected (AU)	Active Detected (AD)

New Markov models and probability transfer functions

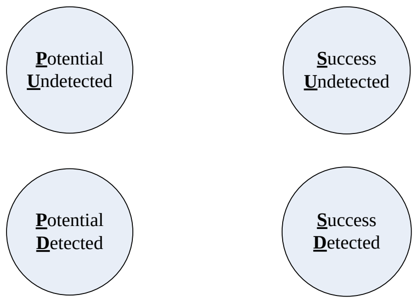
New definitions – e.g. the Attacker Action leaf



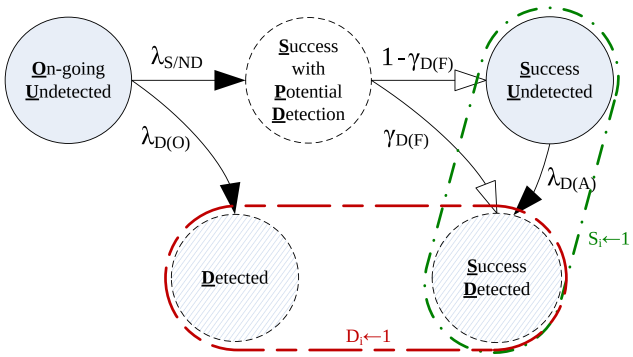
Attacker Action (AA)

Markov processes

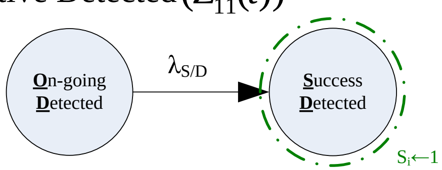
Idle $(Z_0^i(t))$



Active Undetected $(Z_{10}^i(t))$



Active Detected $(Z_{11}^i(t))$



Probability transfer functions

$f^i_{0\to 10}(PU)=\{Pr(OU)=1-\gamma_{D(I)}, Pr(D)=\gamma_{D(I)}, Pr(SD)=0, Pr(SU)=0\}$

$(PD)=\{Pr(OU)=0, Pr(D)=1, Pr(SD)=0, Pr(SU)=0\}$

$(SU)=\{Pr(OU)=0, Pr(D)=0, Pr(SD)=0, Pr(SU)=1\}$

$(SD)=\{Pr(OU)=0, Pr(D)=0, Pr(SD)=1, Pr(SU)=0\}$

$f^i_{0\to 11}(PU)=\{Pr(OD)=1, Pr(SD)=0\}^*$

$(PD)=\{Pr(OD)=1, Pr(SD)=0\}$

$(SU)=\{Pr(OD)=0, Pr(SD)=1\}^*$

$(SD)=\{Pr(OD)=0, Pr(SD)=1\}$

$f^i_{10\to 11}(OU)=\{Pr(OD)=1, Pr(SD)=0\}^*$

$(D)=\{Pr(OD)=1, Pr(SD)=0\}^{**}$

$(SD)=\{Pr(OD)=0, Pr(SD)=1\}^{**}$

$(SU)=\{Pr(OD)=0, Pr(SD)=1\}^*$

$f^i_{11\to 0}(OD)=\{Pr(PU)=0, Pr(PD)=1, Pr(SD)=0, Pr(SU)=0\}$

$(SD)=\{Pr(PU)=0, Pr(PD)=0, Pr(SD)=1, Pr(SU)=0\}$

$f^i_{10\to 0}(OU)=\{Pr(PU)=1, Pr(PD)=0, Pr(SD)=0, Pr(SU)=0\}$

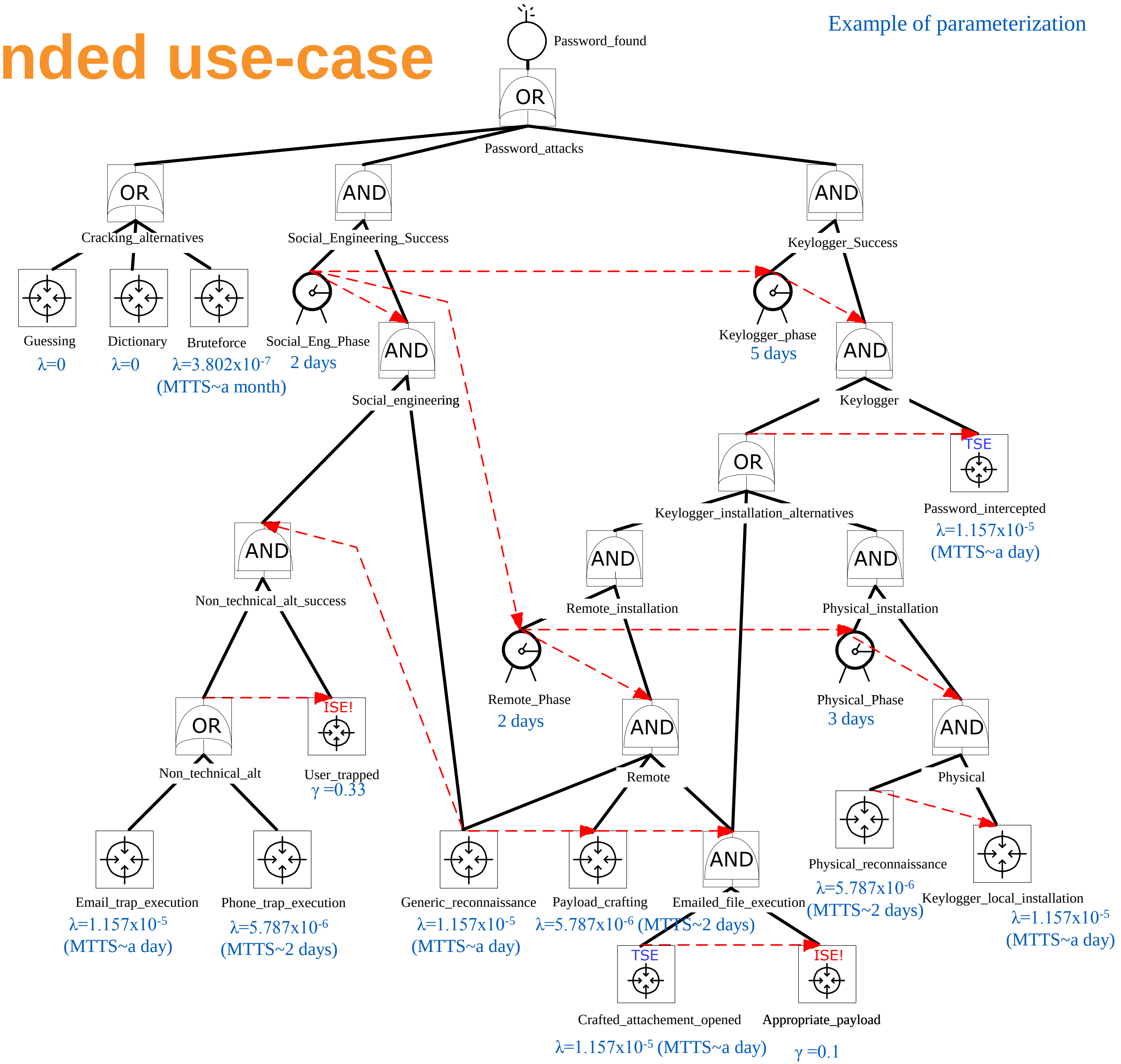
$(SU)=\{Pr(PU)=0, Pr(PD)=0, Pr(SD)=0, Pr(SU)=1\}$

** The detection has occured at a different leaf*

*** Despite D and SD having null durations, these lines are necessary to specify the transfer function, the transfer being potentially triggered by the leaf itself.*

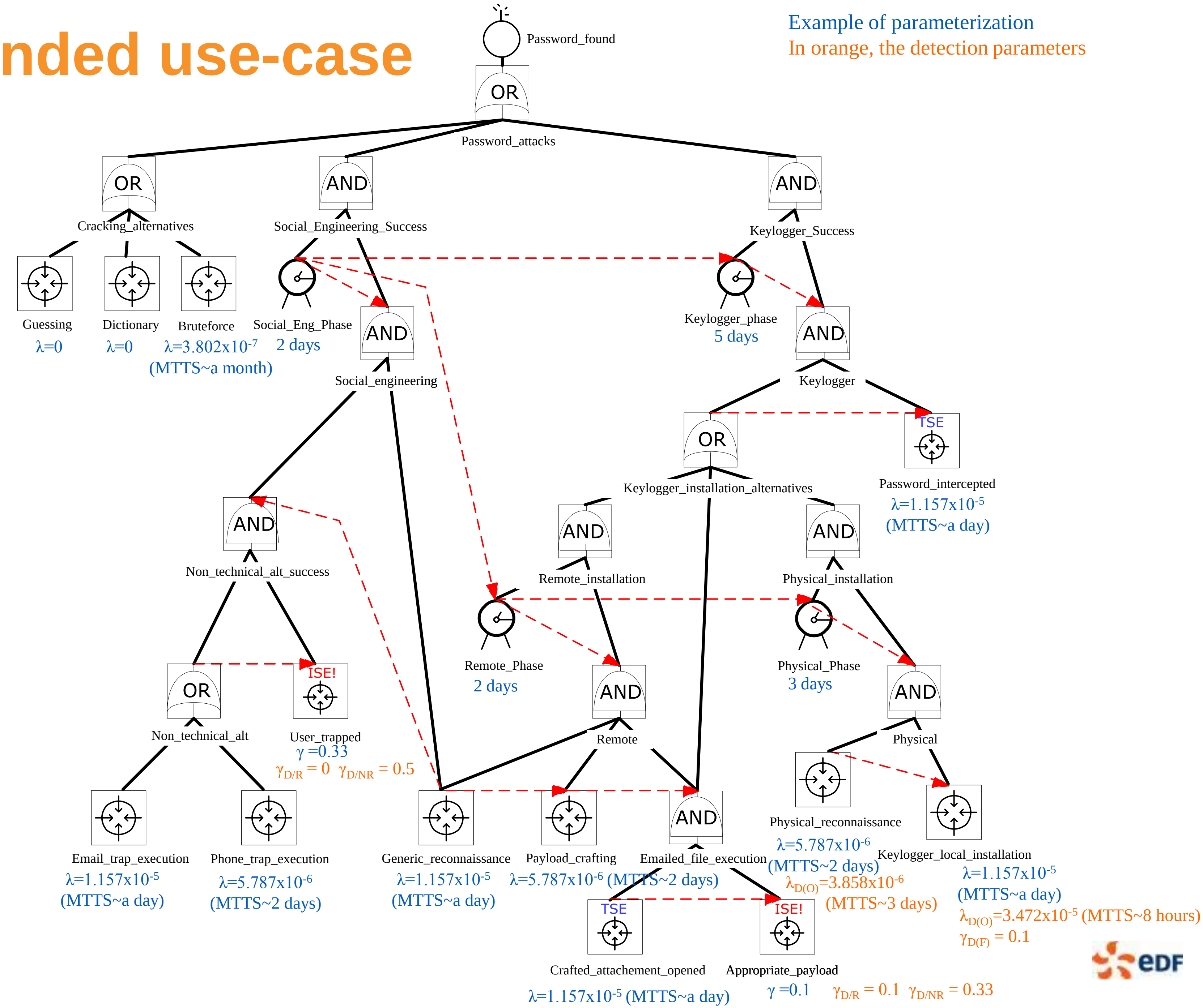
Extended use-case

Example of parameterization



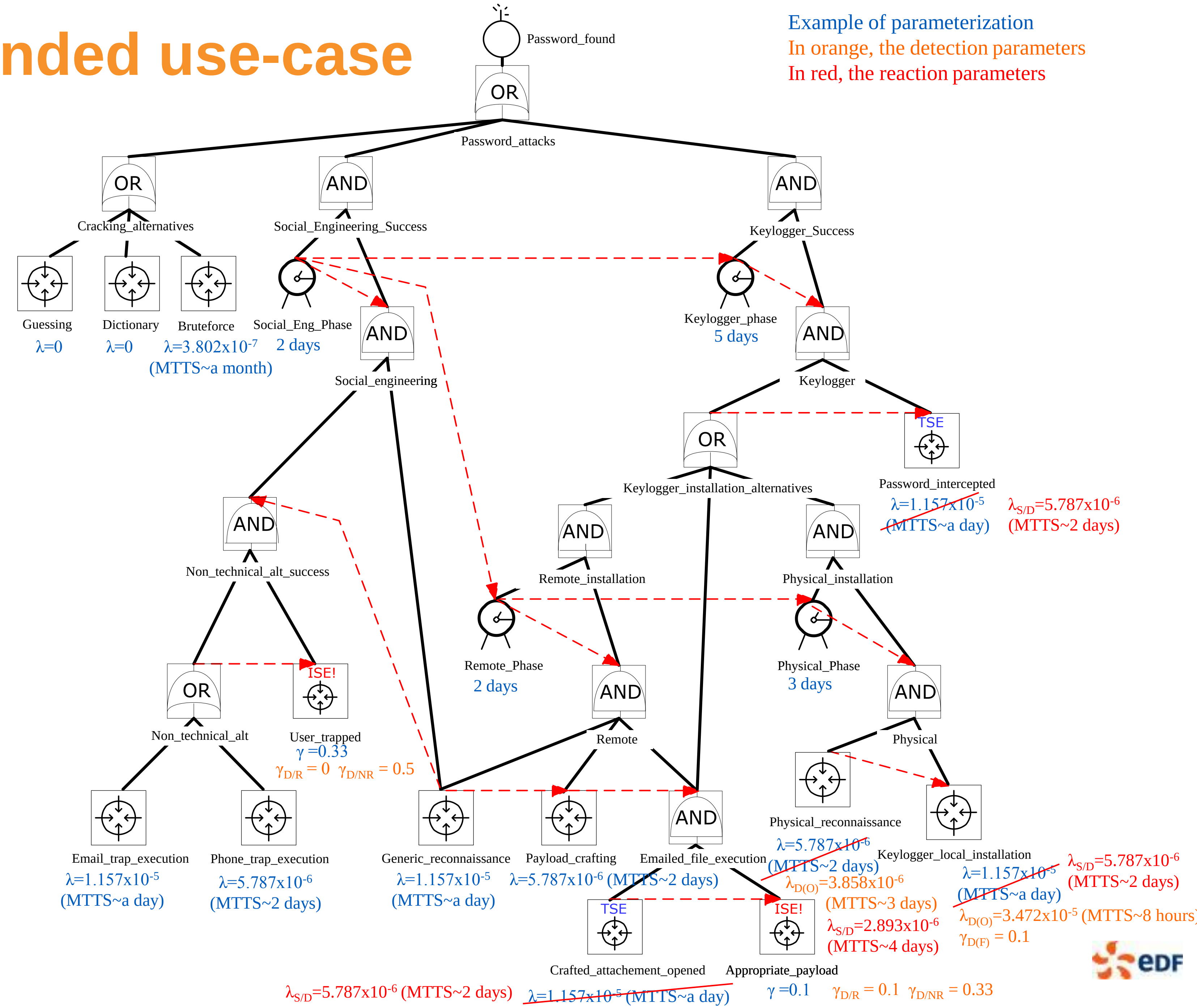
Extended use-case

Example of parameterization
In orange, the detection parameters



Extended use-case

Example of parameterization
In orange, the detection parameters
In red, the reaction parameters



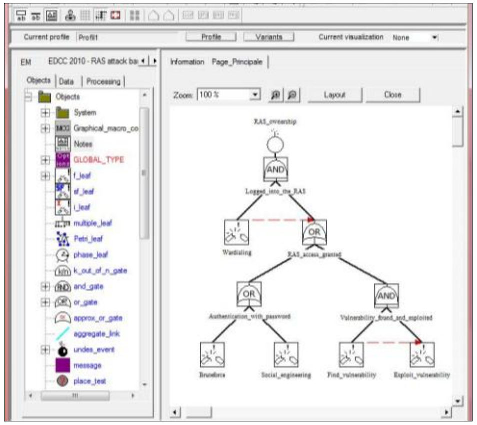
Typical results

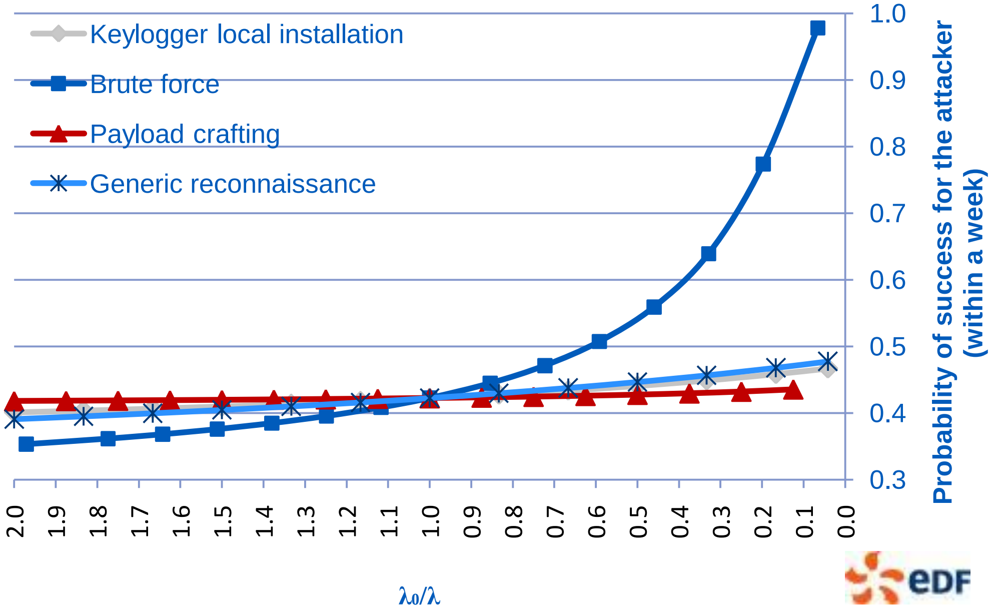
- Probability of success within a week: 0.364 (-14 %)
- Representative sequences (4231 vs 656)

	Sequences	Probability in a week	Average duration	Contrib.
1	<Social Eng>Generic reconn., Email trap exec., User trapped	1.091×10^{-1}	9.889×10^{4}	30.0%
2	<Social Eng>Generic reconn., Phone trap exec., User trapped	5.456×10^{-2}	9.889×10^{4}	15.0%
3	Bruteforce	2.144×10^{-2}	5.638×10^{4}	5.9%
4	<Social Eng>*Generic reconnaissance*, Bruteforce	1.055×10^{-2}	9.889×10^{4}	2.9%
...	([...], Bruteforce) × 9			
14	<Social Eng><Social Eng><Keylogger><Remote>Generic reconnaissance, Payload crafting(no detection), Appropriate payload(no detection), Password intercepted	2.250×10^{-3}	2.761×10^{5}	0.6%
...	([...], Bruteforce) × 2			
17	<Social Eng>Generic reconnaissance <Social Eng><Keylogger><Remote>Payload crafting(no detection), Appropriate payload(no detection), Password intercepted	1.923×10^{-3}	2.688×10^{5}	0.5%
...	([...], Bruteforce) × 2			
20	<Social Eng>*Generic reconnaissance, Email trap exec., User trapped(failure and detection)* <Social Eng><Keylogger><Remote><Remote> <Physical>Physical reconn., Keylogger local installation, Password intercepted	1.549×10^{-3}	5.991×10^{5}	0.4%

Recent advances and on-going work

- Extension of the KB3 software suite
  - Security-oriented "knowledge basis" (Figaro)
  - Directly usable by analysts
- Assist the analyst in security decisions
  - Sequences discrimination on attacker profile
  - Sequences presentation
  - Sensitivity analysis
- Safety and Security
  - Integrated models
  - Interdependenncies





Perspectives

- Enhance usability
  - (Internal) users feedback
  - Develop the side-tools (sensitivity script HMI, etc.)
  - Attack patterns library
- Theoretical extensions
  - Experiment different probability distributions (e.g., McQueen *et al.*)
  - Integration with Bayesian networks
  - Many attack trees extensions could be adapted
    - Intervals, fuzzy sets, OWA gates
    - Game theory
    - Etc.

Conclusion

- Graphical security modeling
  - Different balances between readability, scalability, modeling power and quantification capabilities
- A adaptation of BDMP to security modeling
  - An original and attractive trade-off
  - With a sound mathematical framework
  - Already an operational formalism
- Inherent limits
  - Attacker behavior stochastic modeling – subjective probabilities
  - More generally, security and quantitative assessments
  - Complementary tool for the security analyst

Some references

On BDMP & KB3

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Thank you for your attention!

Большое спасибо

Questions & Answers