EEMCS - SCS

EVOLUTIONARY ALGORITHMS FOR CYBERSECURITY

GUEST LECTURE – APRIL 3, 2025

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SUMMARY

- Intro to Cybersecurity
- Cryptography & EA
- Network Intrusion Detection & EA

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INTRO TO CYBERSECURITY

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THE CIA TRIAD OF SECURITY

When building a secure system, we focus on three aspects [1]:

Confidentiality

Data are protected from unauthorized access/use

Integrity

Data have not been altered by unauthorized parties

Availability

Data are available to authorized parties when needed

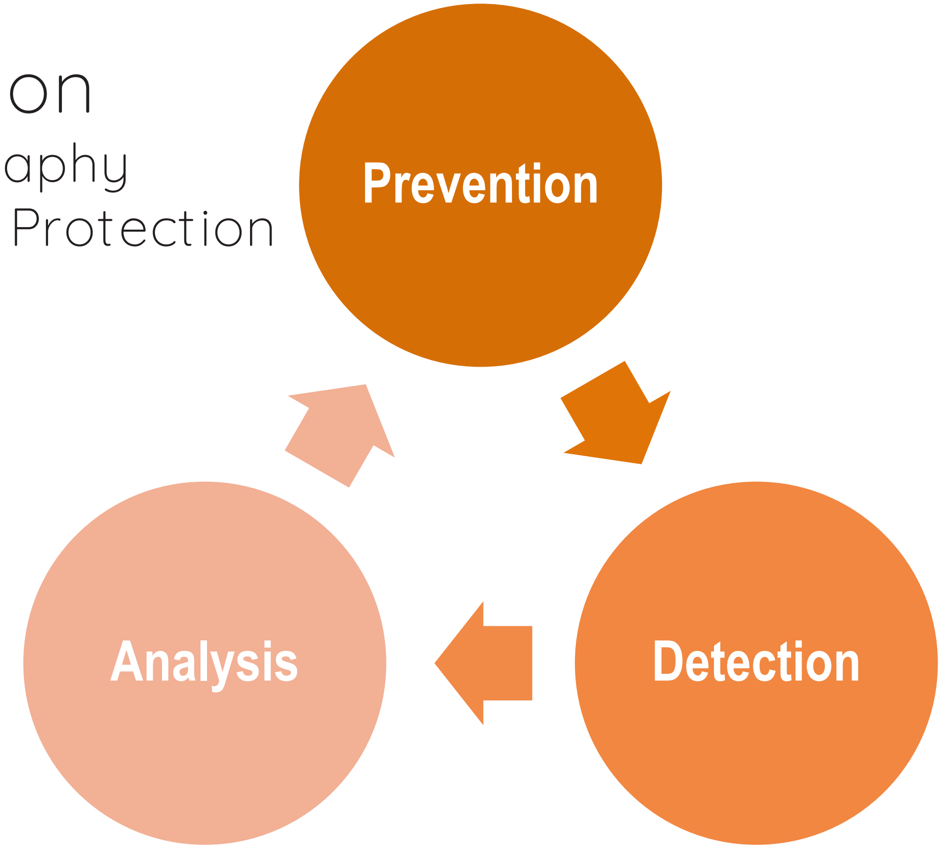
THREAT MODELING

- Threat: potential violation of a security goal
- Attack: intentional violation of a security goal
- Security: protection from attacks vs. cost

Security is economics!

ACHIEVING SECURITY

Prevention
- Cryptography
- Intrusion Protection



Detection
- Intrusion Detection
- Malware Detection

Analysis
- Forensics
- Incident Response

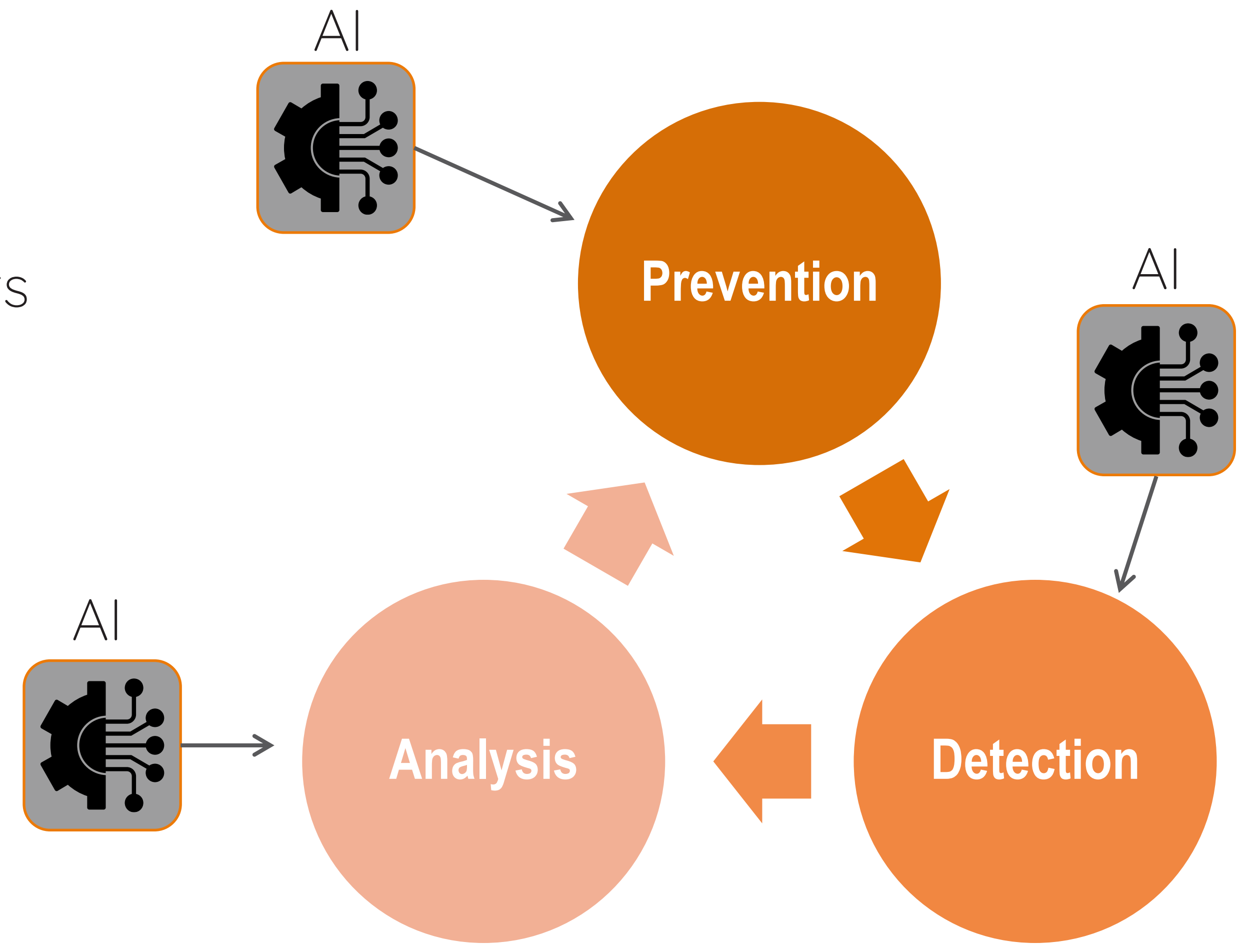
AI FOR SECURITY

Challenges:

- New vulnerabilities, new attack vectors
- Reducing human intervention

Approach: “Smarter” Security

- Automate the design process
- Use AI techniques (e.g. Evolutionary Computing) for the automation



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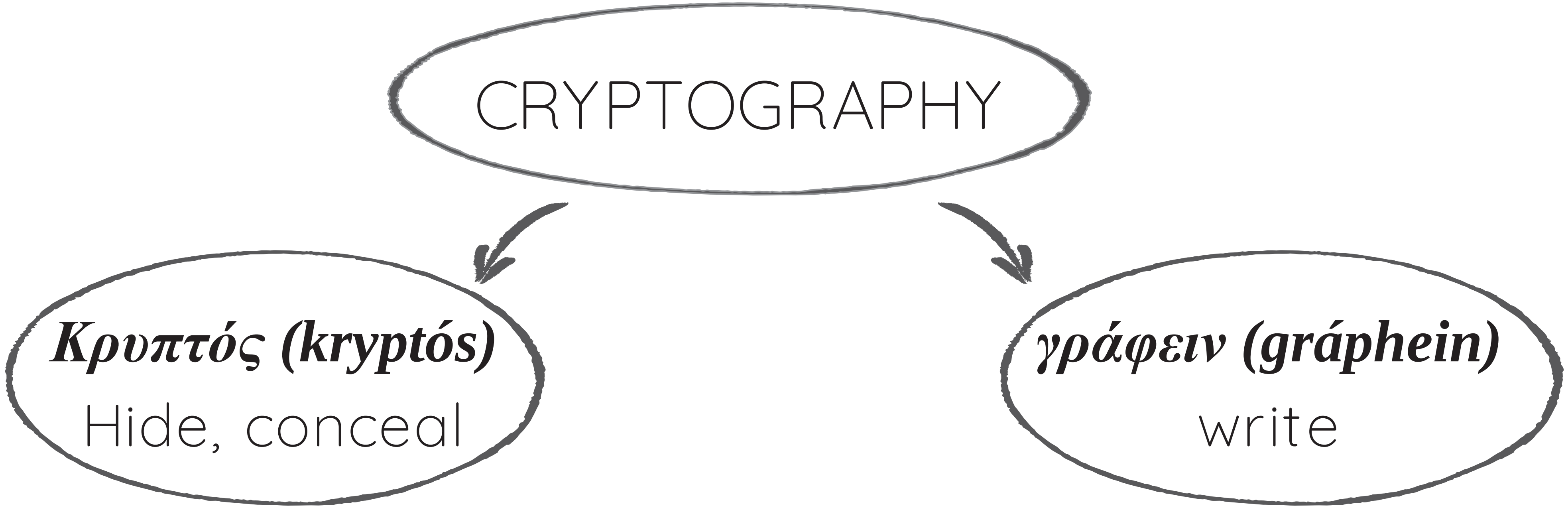
CRYPTOGRAPHY

WHAT IS CRYPTOGRAPHY?



Historically: the art of hiding the meaning of messages, with the goal of protecting their confidentiality

THE CIA TRIAD IN CRYPTOGRAPHY

In cryptography, the "A" is usually replaced by Authenticity:

Confidentiality

Data are protected from unauthorized access/use

Integrity

Data have not been altered by unauthorized parties

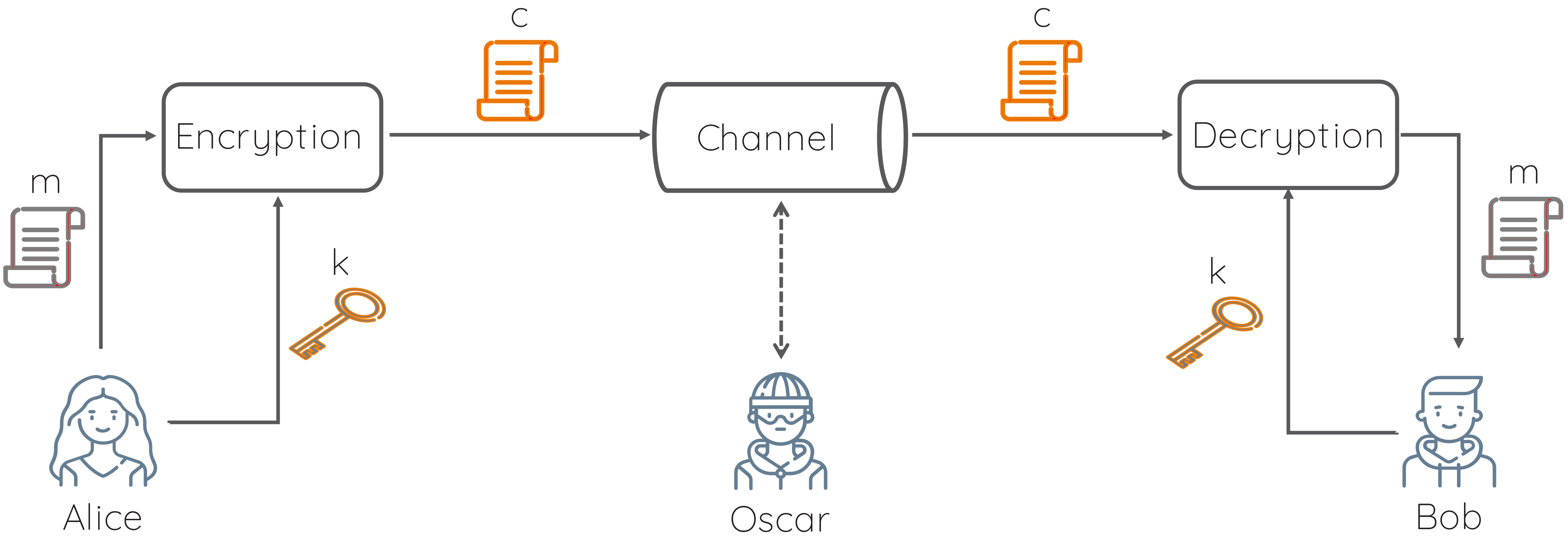
Authenticity

Data have been created by the intended party

Confidentiality → Encryption schemes

Integrity, Authenticity → Authentication codes, Digital signatures

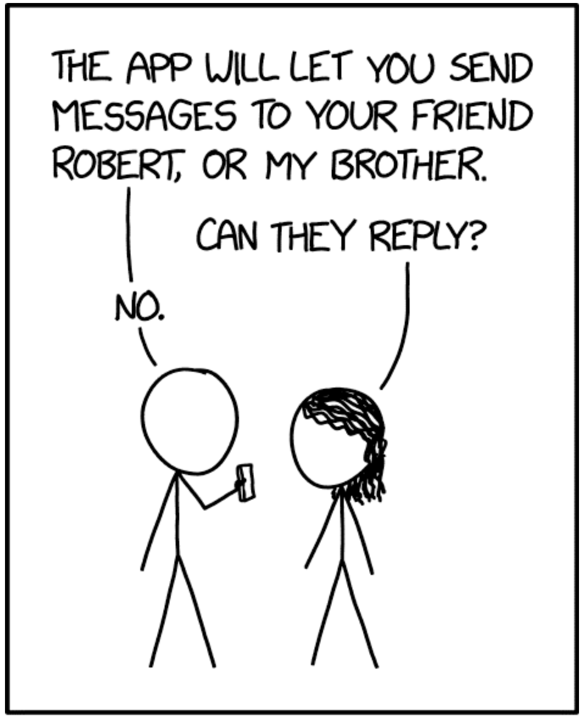
SYMMETRIC-KEY ENCRYPTION SCENARIO



m: plaintext message   k: encryption/decryption key   c: ciphertext message

SYMMETRIC-KEY ENCRYPTION SCENARIO

- The same key k is used both for encryption *and* decryption [6]
- The scheme is "secure" as long as Oscar does not know k
- Requires sharing k *before* communicating
- Here, we just assume Alice and Bob shared k somehow



MY NEW SECURE TEXTING APP ONLY ALLOWS PEOPLE NAMED ALICE TO SEND MESSAGES TO PEOPLE NAMED BOB.

KERCHOFFS'S PRINCIPLE (1883)

- The encryption scheme is known to the attacker [7]
- Security relies *only* on the secrecy of the encryption key

"The encryption/decryption system must not be kept secret, and can be stolen by the enemy without causing any problem."

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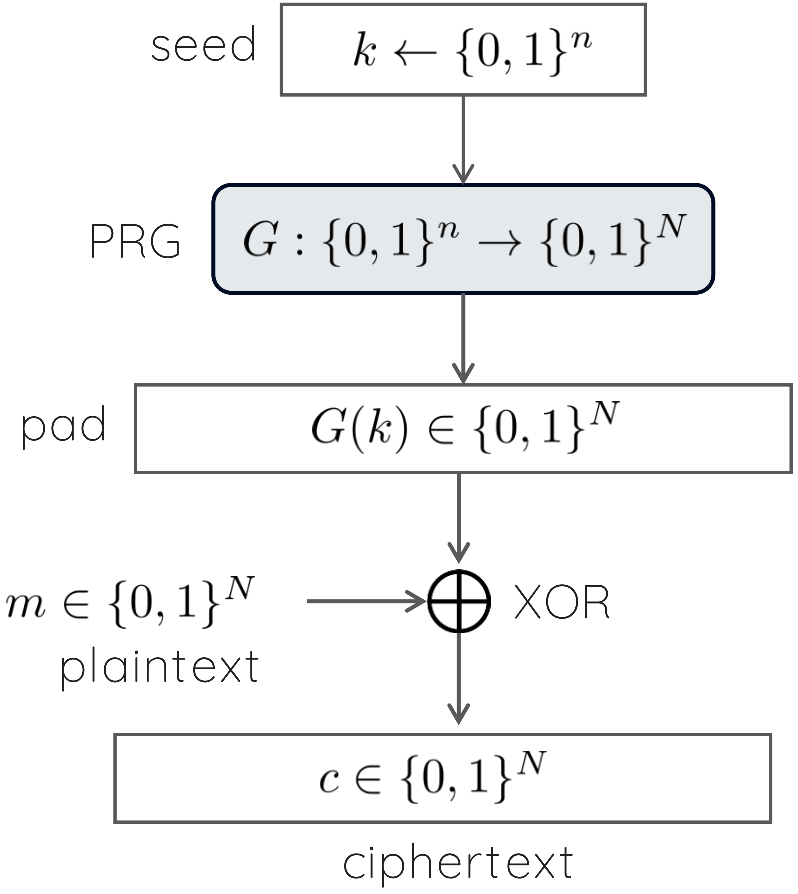
STREAM CIPHERS - ENCRYPTION

- Idea: Alice encode all messages as stream of bits, $m \in \{0,1\}^N$
- A Pseudo Random Generator (PRG) is used to generate a pad $p \in \{0,1\}^N$ of the same length of the message [6]
- The seed of the PRG is the key $k \leftarrow \{0,1\}^n$
- Encryption: Bitwise XOR between message and pad

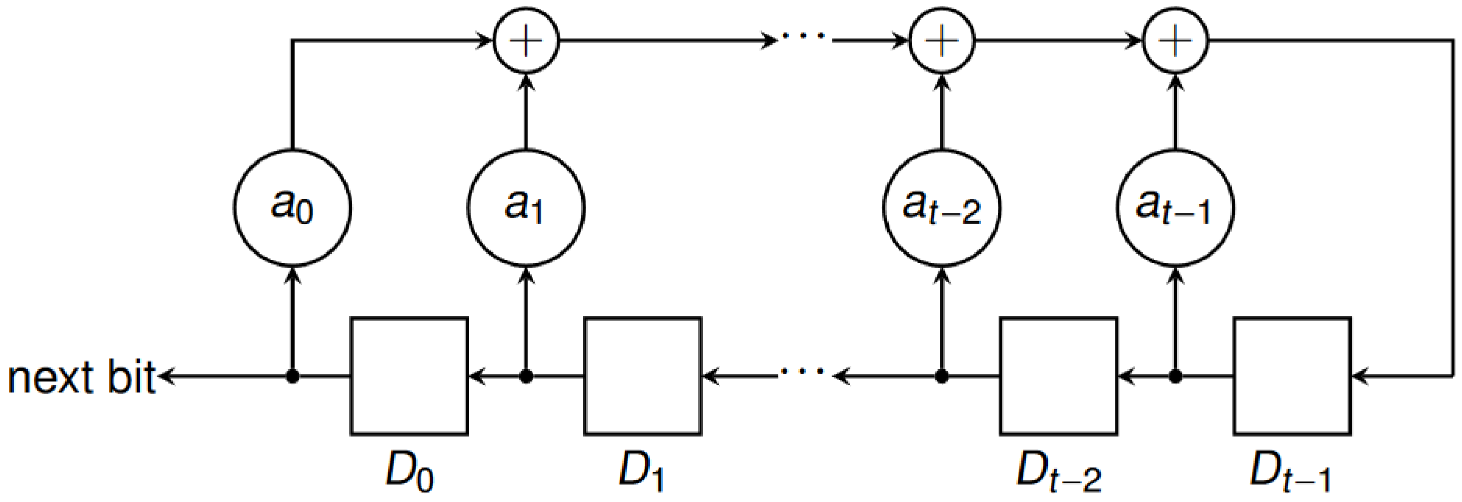
$$c_i := m_i \oplus p_i, \text{ for all } i \in \{1, \cdots, N\}$$



LINEAR FEEDBACK SHIFT REGISTERS (LFSR)

- A device computing a *linear recurring sequence* (LRS)

$$z_i = a_0 \cdot z_{i-t} \oplus a_1 \cdot z_{i-t+1} \oplus \cdots \oplus a_{t-1} \cdot z_{i-1} \qquad a_j, z_j \in \{0, 1\}$$



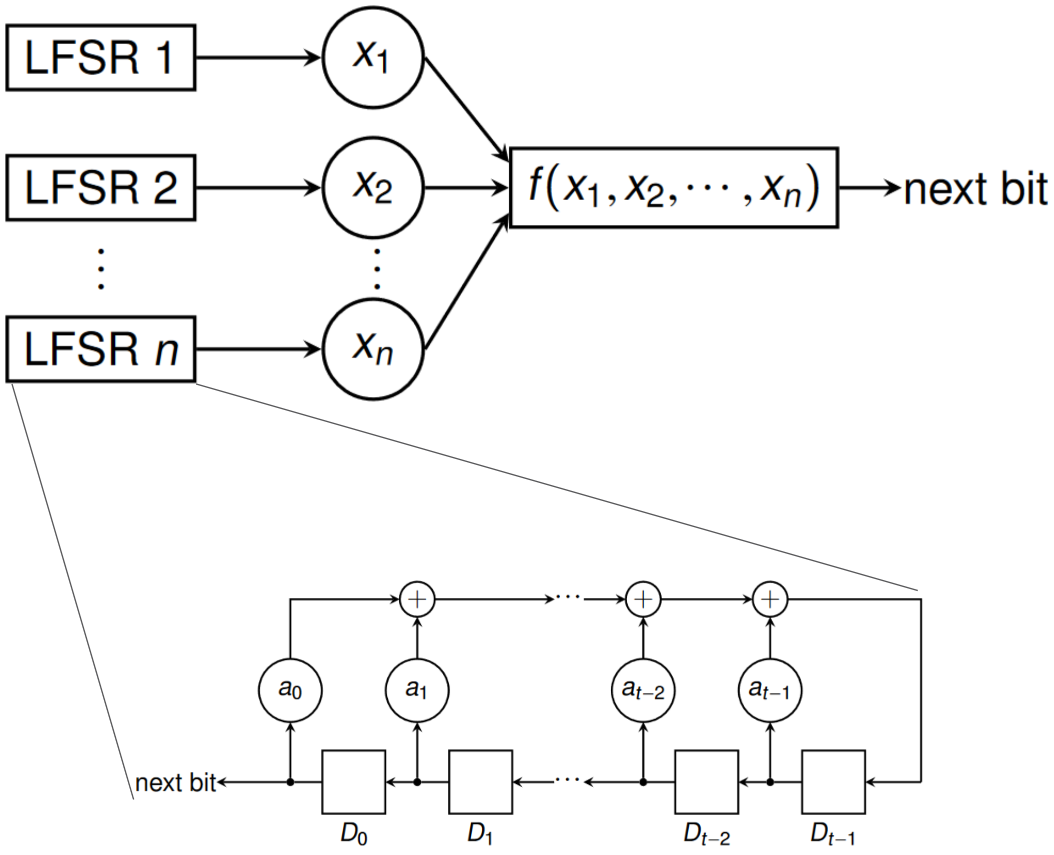
- Problem: very weak as a cryptographic PRG [6]

IMPROVING LFSR – COMBINER MODEL FOR PRG

- Idea: use n LFSRs instead of one [4]
- LFSRs outputs *combined* using a Boolean function:

$$f : \{0,1\}^n \rightarrow \{0,1\}$$

- Security of the PRG: cryptographic properties of $f : \{0,1\}^n \rightarrow \{0,1\}$



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BOOLEAN FUNCTIONS

- A mapping $f : \{0,1\}^n \rightarrow \{0,1\}$ represented by a *truth table*

(x_1, x_2, x_3)	000	001	010	011	100	101	110	111
$f(x_1, x_2, x_3)$	0	1	1	0	1	0	1	0

- The function must satisfy some properties to resist specific attacks [4]:
  - Balancedness (equal number of 0s and 1s)
  - High Nonlinearity (Hamming distance from linear functions)
  - High algebraic degree, etc. …

EVOLUTIONARY ALGORITHMS FOR BOOLEAN FUNCTIONS

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OPTIMIZATION PROBLEM

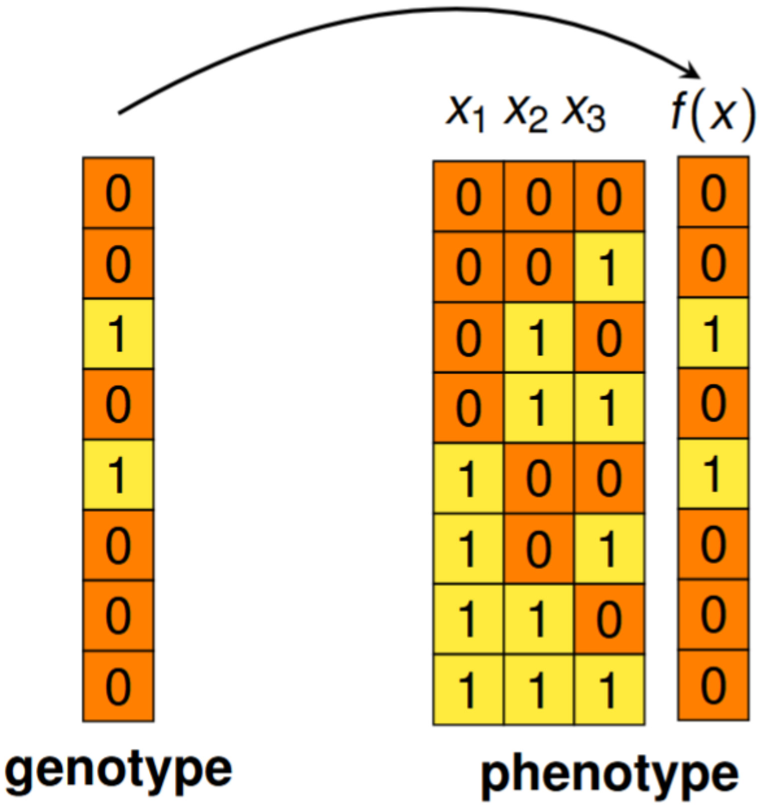
- Given $n \in \mathbb{N}$, how do we fill the table so that f is balanced and highly nonlinear?

(x_1, x_2, x_3)	000	001	010	011	100	101	110	111
$f(x_1, x_2, x_3)$	?	?	?	?	?	?	?	?

$$f^* = \text{argmax}_{f:\{0,1\}^n \to \{0,1\}} (BAL(f) + NL(f))$$

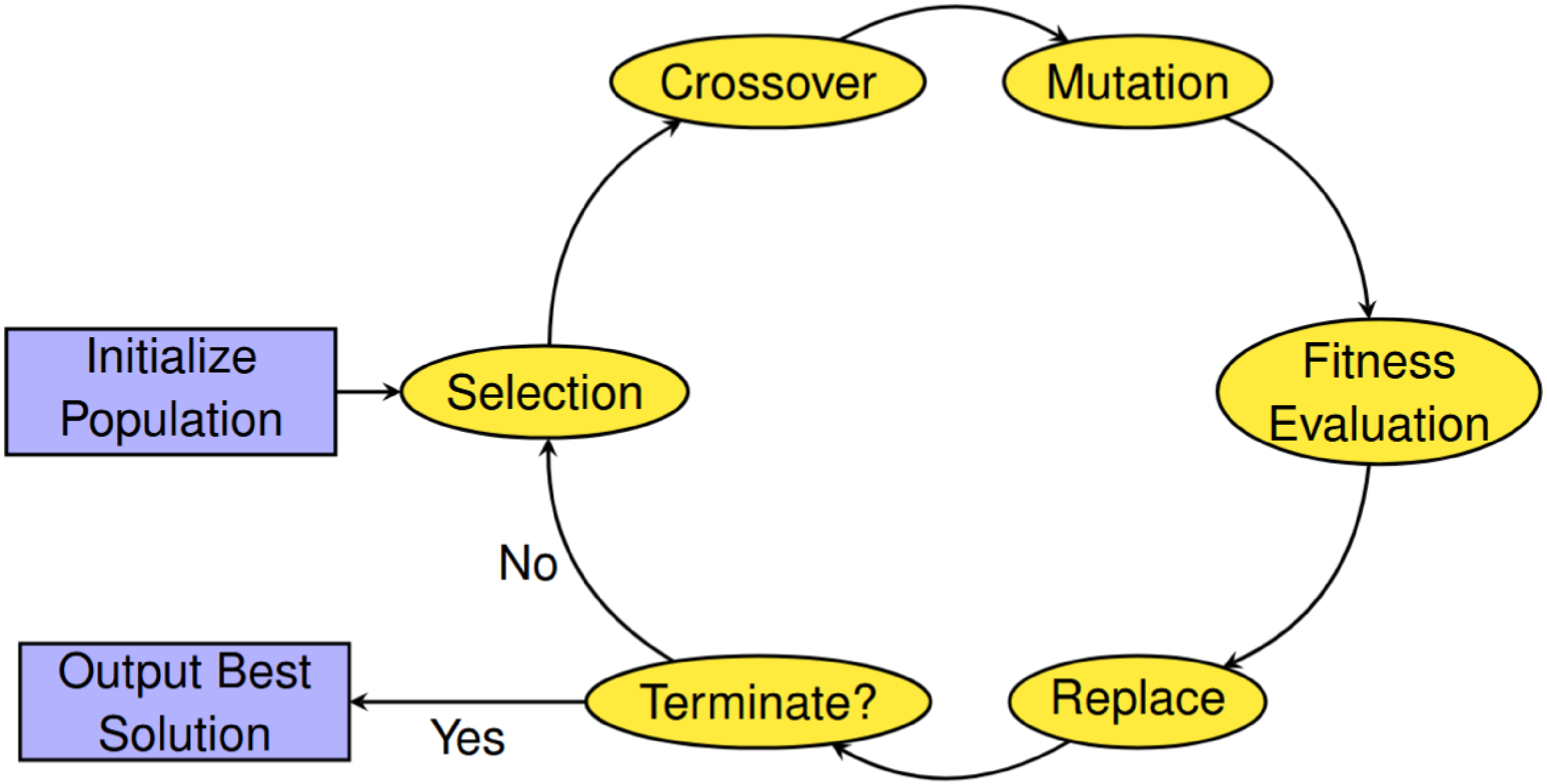
- The truth table has size 2^n so there are 2^{2^n} combinations
- For concrete security, we need $n > 13$
- But exhaustive search is already unfeasible for $n > 5$!

EVOLUTIONARY ALGORITHMS (EA)



- Optimization algorithms loosely based on evolutionary principles
- Genetic Algorithms (GA): introduced by John Holland (1975)
- GA genotype: fixed-length bitstrings
- phenotype: truth table of f [5]

THE EA LOOP



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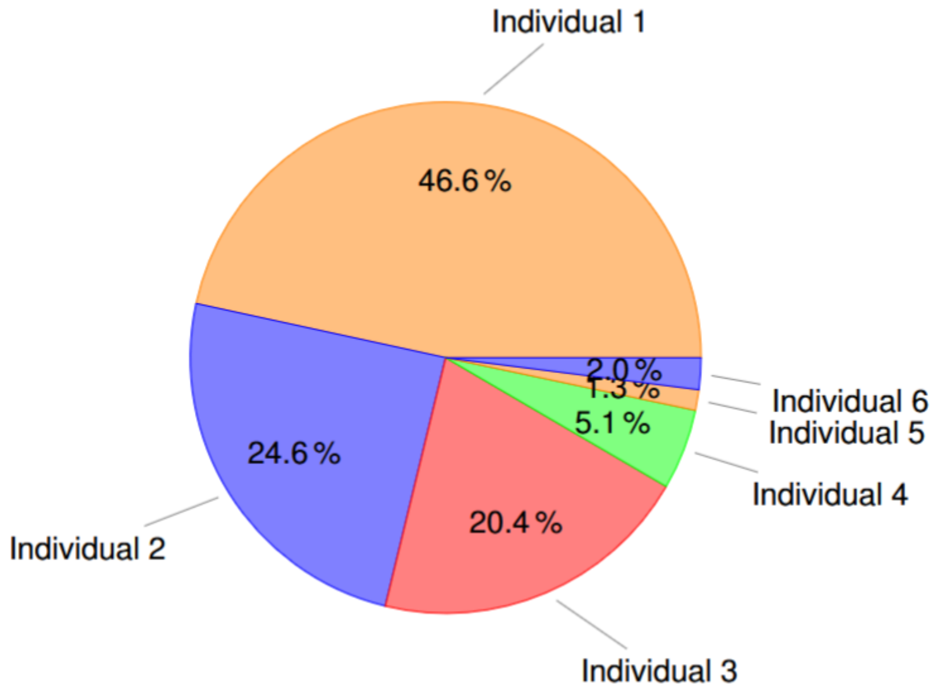
SELECTION



- Roulette-Wheel: selection probability proportional to individual's fitness

- Tournament: select the fittest individual from a random sample of t individuals

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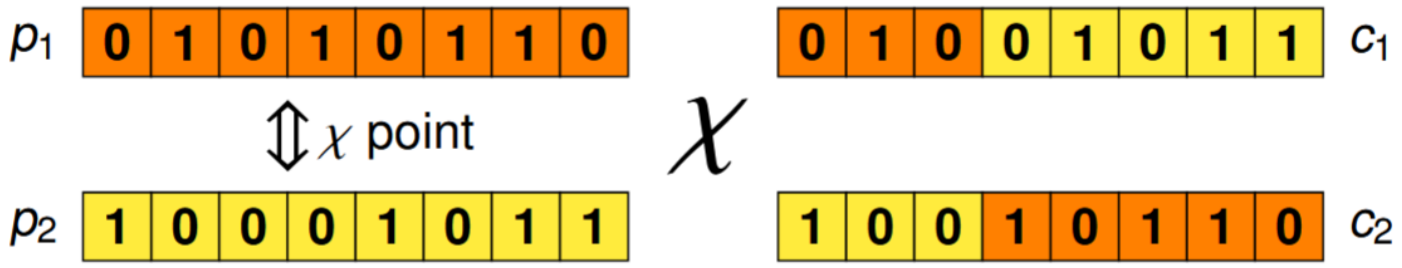
CROSSOVER

- Idea: recombine the genes of two parents (Exploitation)

GA Example: One-Point Crossover

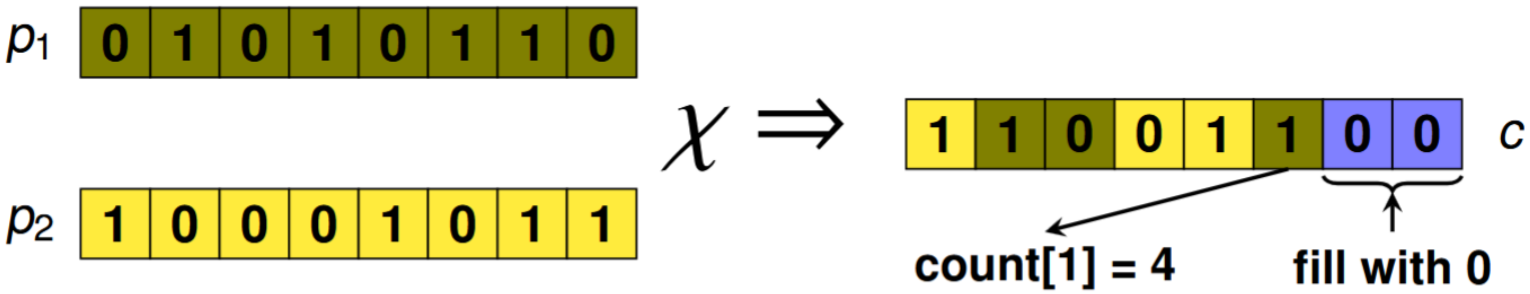


- Problem: how dow we ensure balancedness for cryptography?
- We could optimize it in the fitness function…

BALANCED CROSSOVER

- Idea: use counters to keep track of the numbers of 1s in the child [9, 13]

GA Example: Counter-based Crossover



- If we start from balanced parents, we get balanced children

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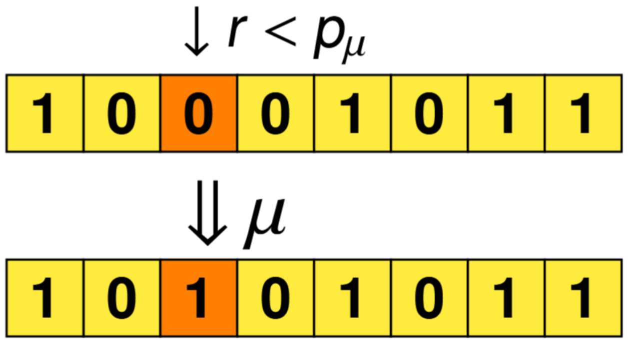
MUTATION

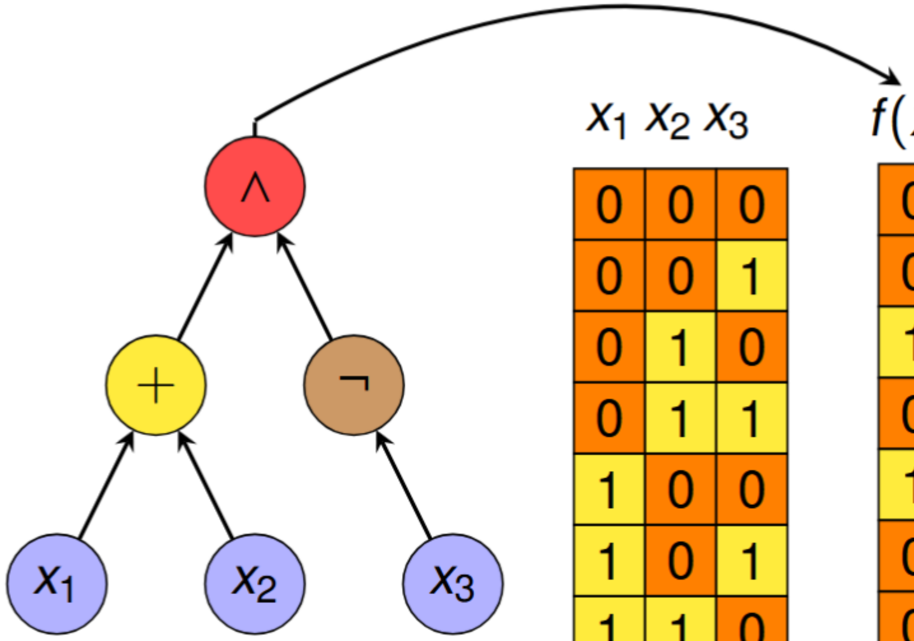
- Idea: introduce new "genetic material" in the offspring (Exploration)

GA Example: Bit-flip mutation



- For balancedness: randomly swap some bits instead of flipping them

GENETIC PROGRAMMING (GP)



x_1	x_2	x_3	$f(x)$
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	0

- Idea: evolve computer programs to solve specific tasks
- GP Genotype: a syntactic tree
  - Leaf nodes: input variables
  - Internal nodes: operators (e.g. AND, OR, NOT, XOR, …)
- Phenotype: evaluate the tree for all possible assignments of the leaf nodes

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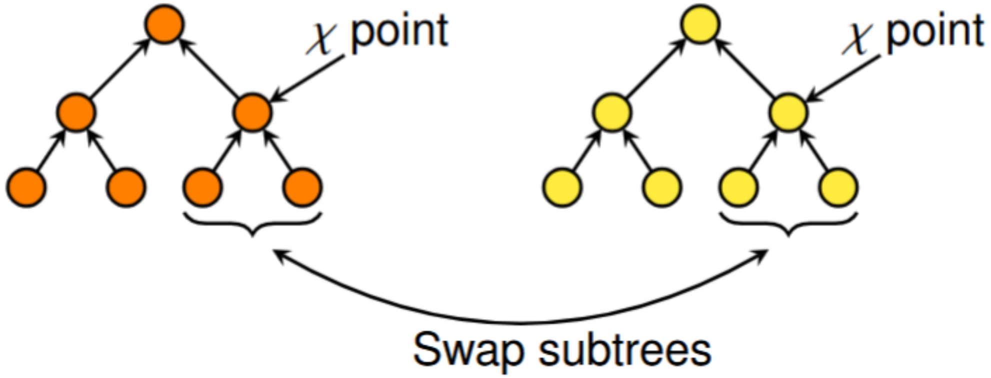
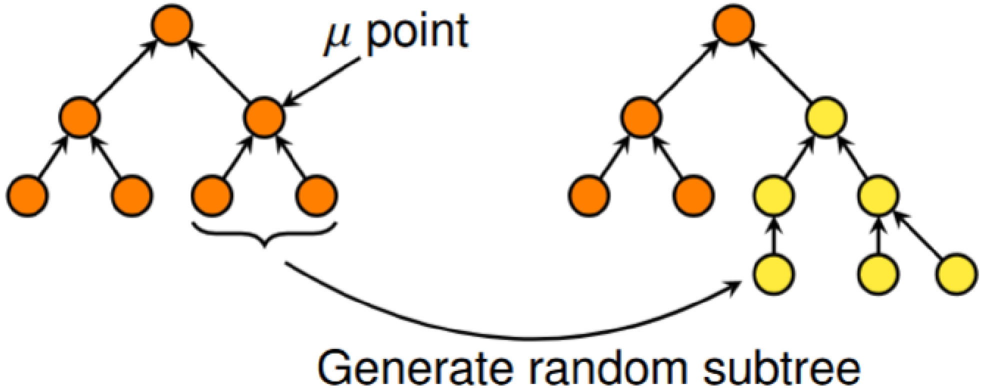
GP CROSSOVER & MUTATION

Subtree Crossover



Subtree Mutation



- In general: not possible to preserve the balancedness of the Boolean function
- Nevertheless: GP usually fares better than (balanced) GA [10, 12, 14, 15]
- Other approaches: use GP to combine existing functions with high nonlinearity [3, 10]

NETWORK INTRUSION DETECTION

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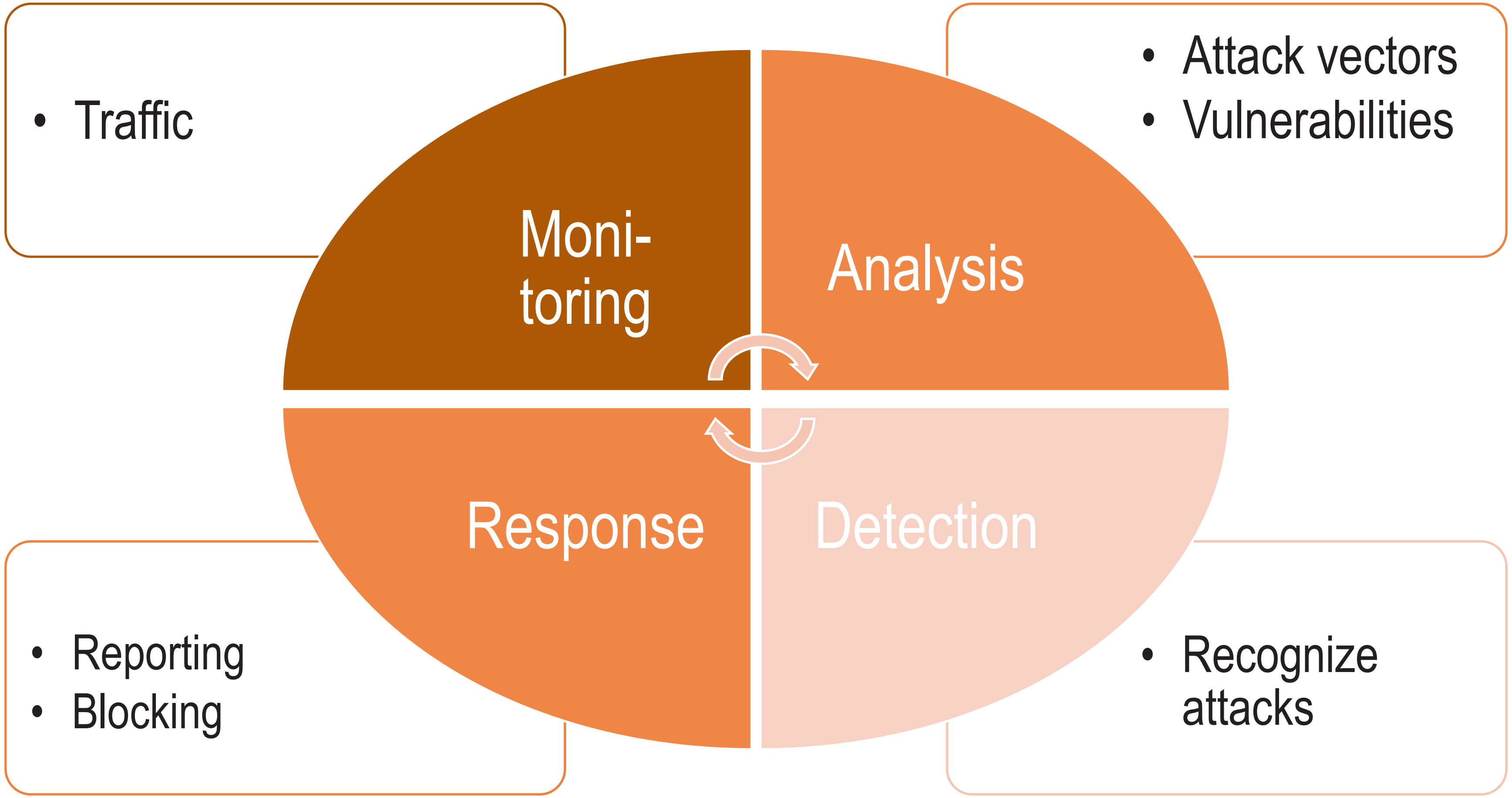
INTRUSION DETECTION

- Intrusion Detection System: Monitoring for attacks
- Attack: attempt to compromise confidentiality, integrity, or availability
- Several types of IDS:
  - Monitor source: network, application, server, …
  - Analysis type: signatures, rules, machine learning, …

NETWORK INTRUSION DETECTION (NIDS)



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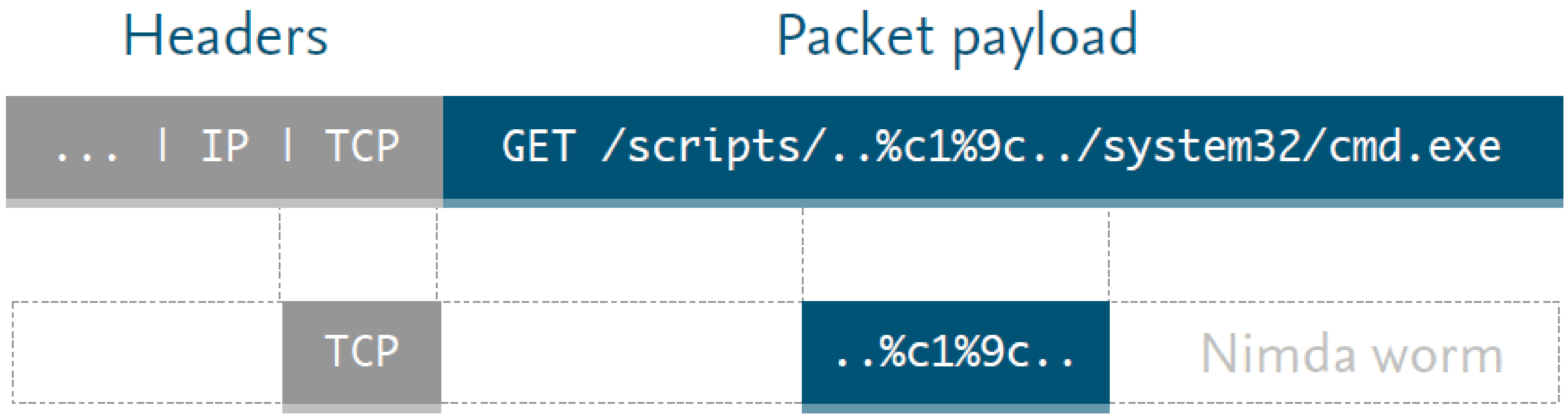
SIGNATURE-BASED NIDS

- Traditional type of NIDS: signature-based [16]

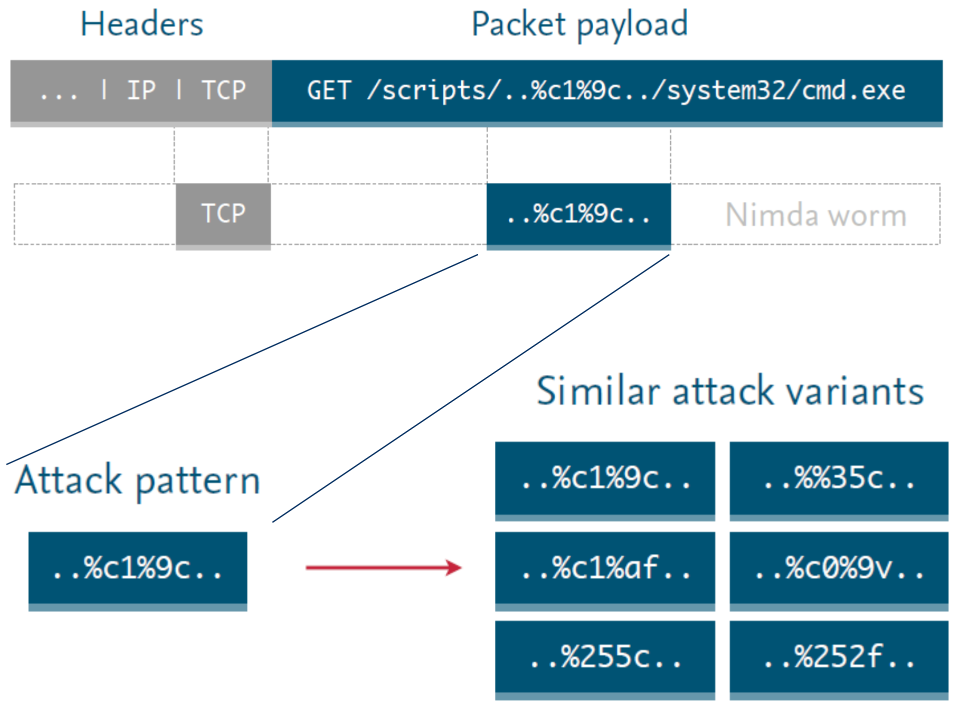


- Leverages pattern detection of known attacks (e.g., with Regular Expressions)

SIGNATURE-BASED NIDS

Common problems:

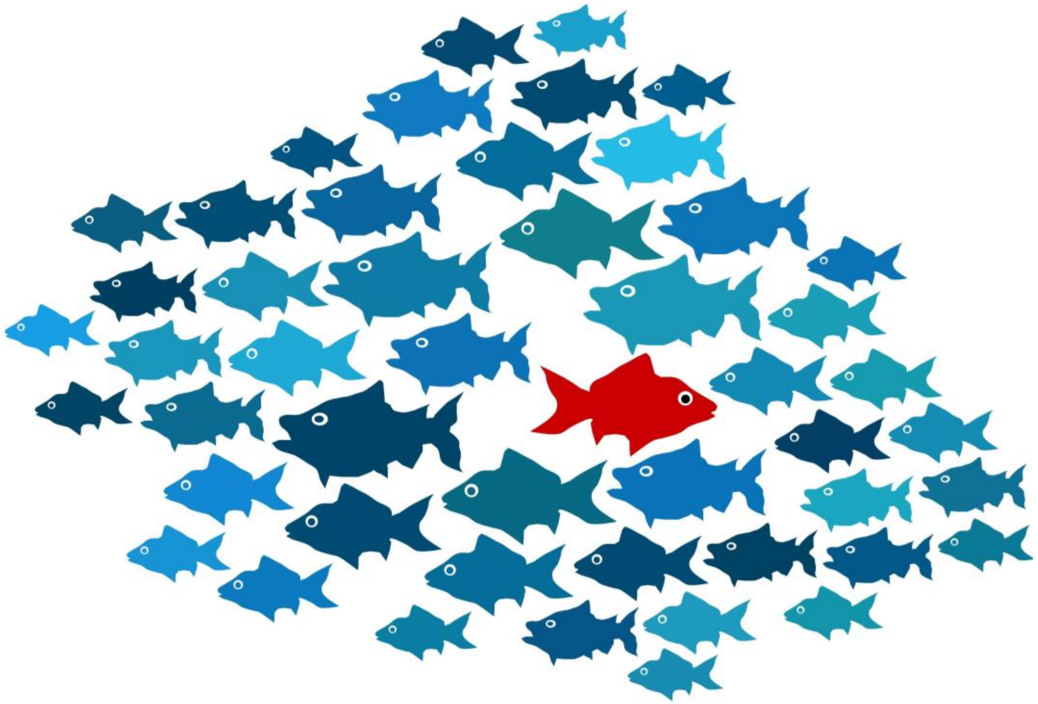
- Signatures from known attacks required
- Signature updates required
- Scalability issues, complexity and attack frequency
- Unable to detect unknown attacks



ANOMALY-BASED NIDS

- Idea: focus on benign traffic only [16]
- Learn a model of “normal” network traffic
- Assumptions:
  - Mainly benign training data
  - Unknown attacks differ from benign data
- Requires careful feature engineering

Easy example: spot the anomalous fish



ANOMALY-BASED NIDS

Another example: who is not Homer?

Features:

1. Size
2. Accessories
3. ...

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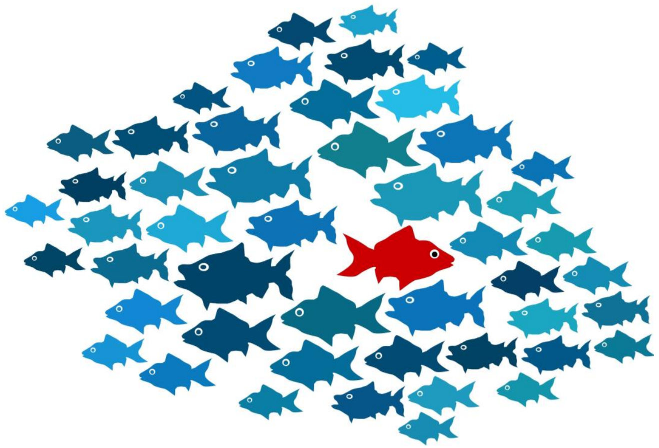
ANOMALY-BASED NIDS

- Risk: detection of irrelevant anomalies as attacks (false positives)
- Choice of features is crucial
- Attacks are deviations from normality
- Various techniques: SVM, KDE, evolutionary algorithms…



ANOMALY-BASED NIDS WITH GENETIC PROGRAMMING

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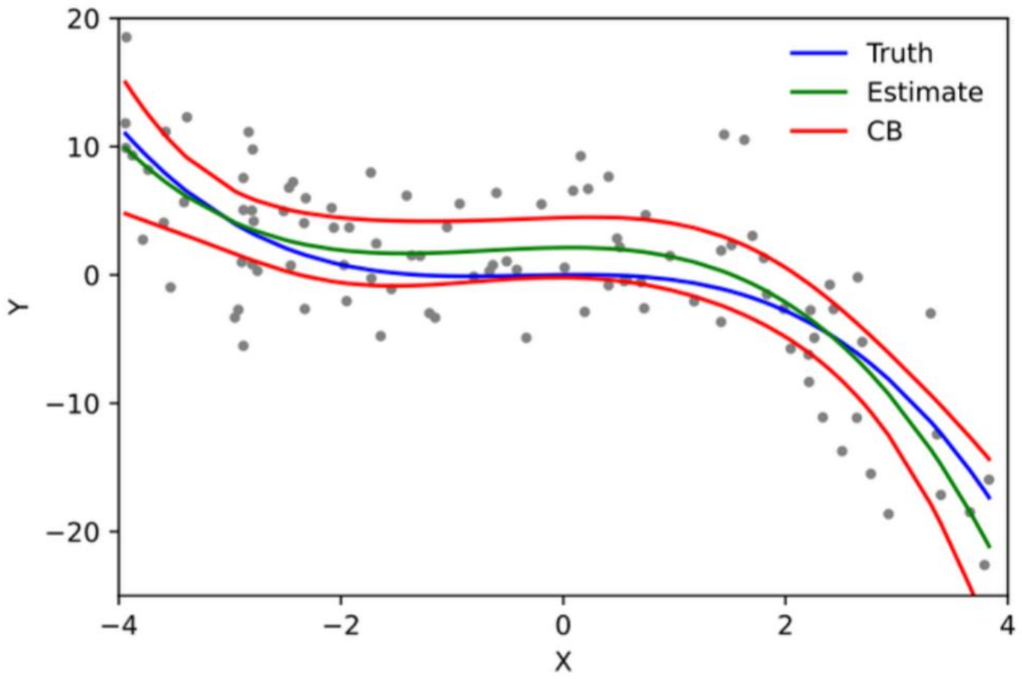
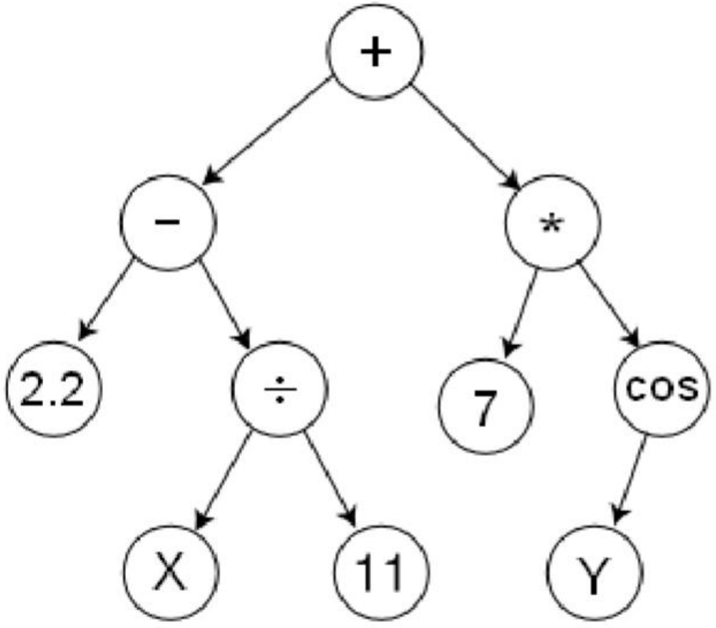
SYMBOLIC REGRESSION WITH GP

- Problem: use GP to find a symbolic expression that minimizes the errors in approximating a given set of data points





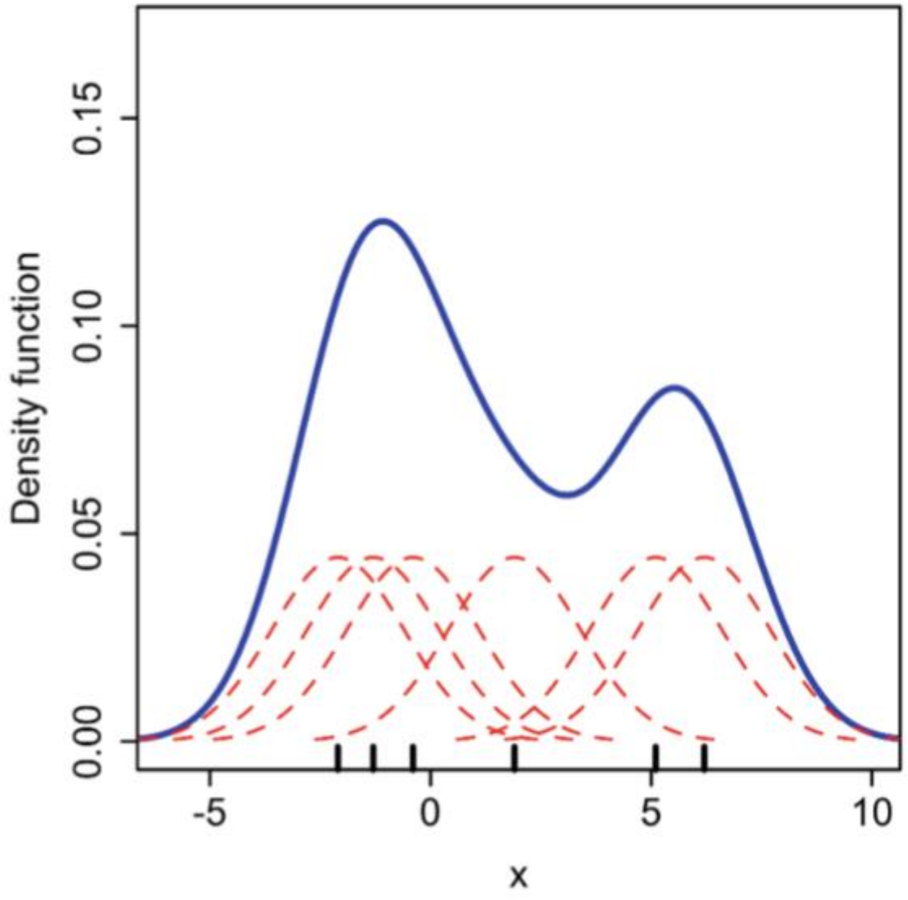
$$\left(2.2 - \left(\frac{X}{11}\right)\right) + \left(7 * \cos(Y)\right)$$

KERNEL DENSITY ESTIMATION FOR NIDS

- Problem: given a dataset of "normal" network packets, identify anomalies
- Possible approach: use kernel density estimation (KDE) [2]
- Given training points $x_1, \cdots, x_n \in \mathbb{R}^d$, estimate the density at x as:

$$\hat{p}(x) = \frac{1}{n} \sum_{i=1}^{n} K_h(x - x_i)$$

where K_h is a kernel function (e.g., a Gaussian distribution



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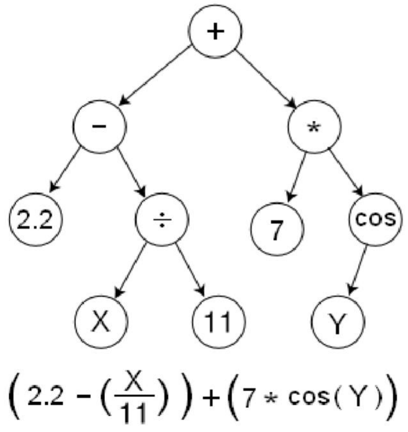
GENETIC PROGRAMMING FOR NIDS

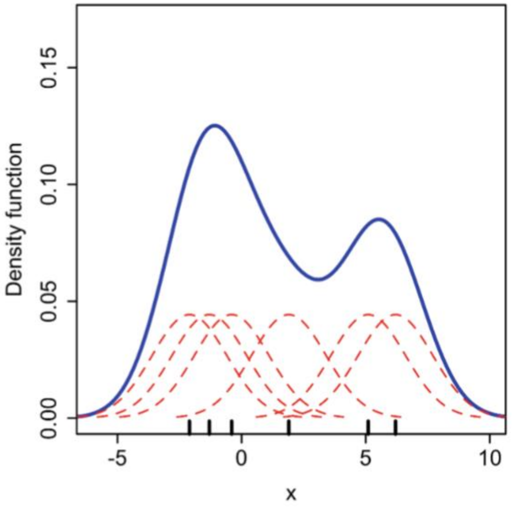
- KDE is expensive to compute at query time
- Need to compute $\hat{p}(x) = \frac{1}{n}\sum_{i=1}^{n} K_h(x - x_i)$ for every new network packet
- Idea: use GP to learn a surrogate f that approximates well the density [2]:

$$f(x_i) \approx d(x_i)$$

- Symbolic regression problem:

$$fit(f) = \sqrt{\frac{\sum_{i=1}^{n}(f(x_i) - d(x_i))^2}{n}}$$





SUMMARY

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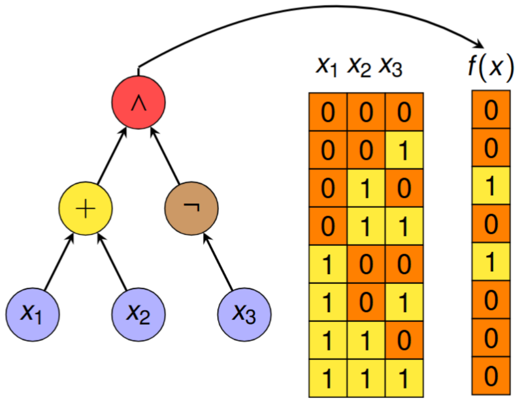
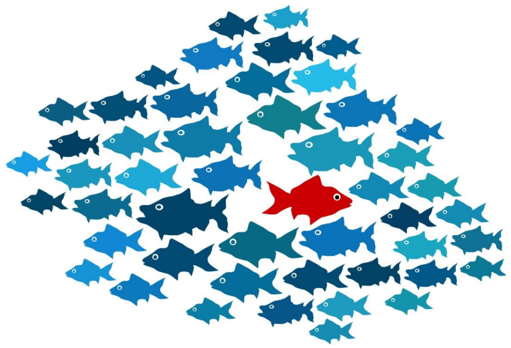
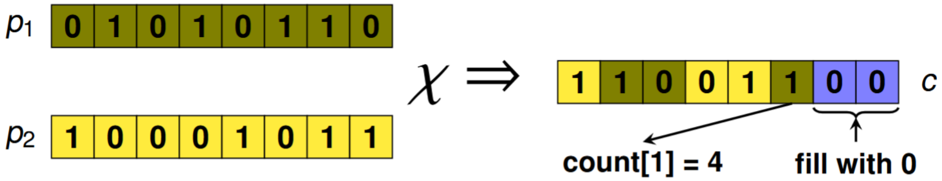
CONCLUDING THOUGHTS

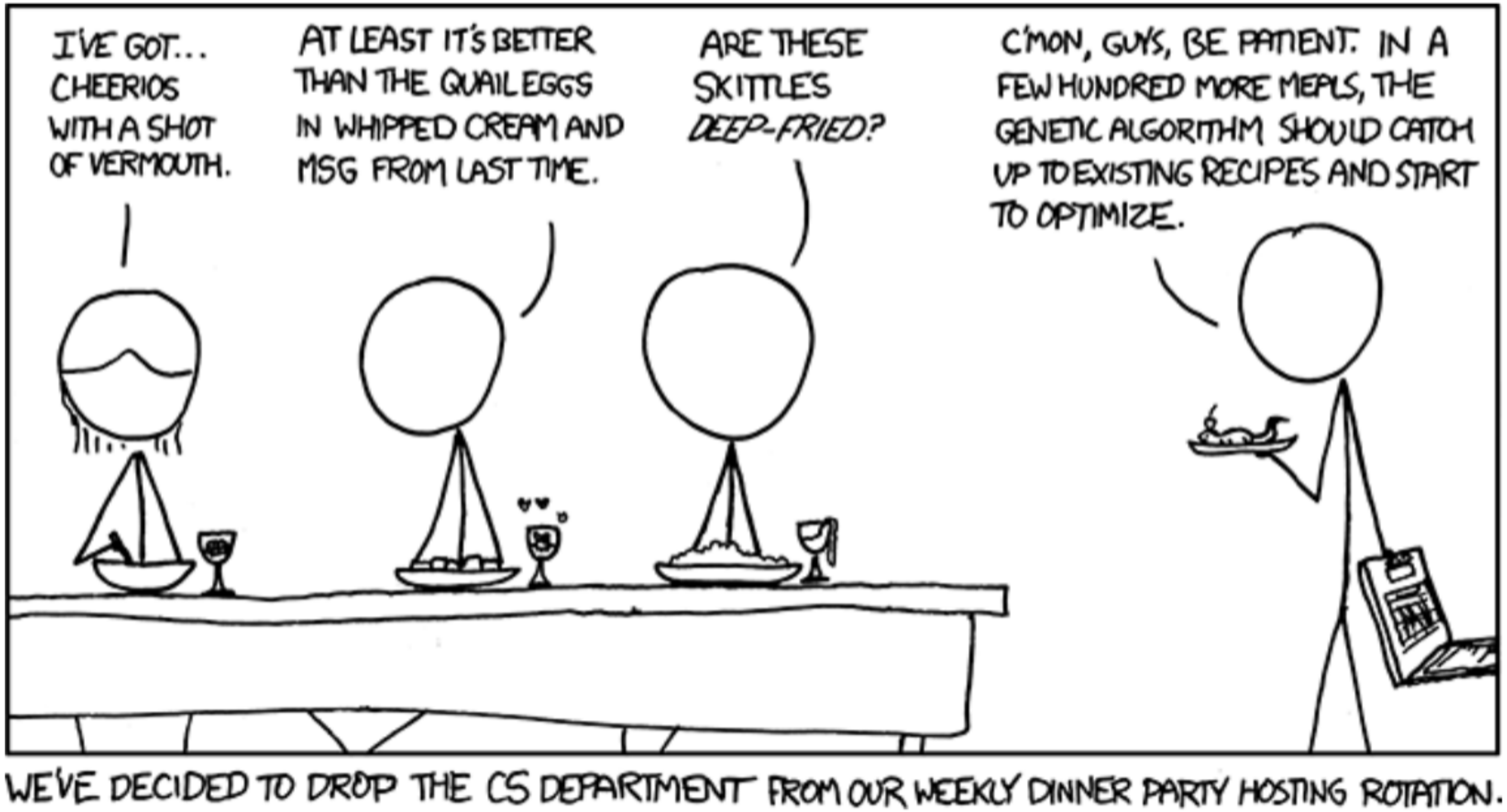
- EA are quite versatile to solve different problems in cybersecurity
- Examples seen here:
  - Cryptography
  - Network Intrusion Detection
- Many other applications!
  - Side-channel analysis [17]
  - Adversarial learning [18]
  - …







THANKS!
QUESTIONS?



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