Analyzing Functional Entropy of Software Intent Protection Schemes

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Why Do We Try to Protect Software?

- Because Programs are Attacked….
- Protect Integrity
  - Decomposing/reusing code
  - Adding new functionalities
- Protect Intent
  - Alter existing functionality
  - Prevent "gaming" functionality
  - Prevent countermeasures
- Protect Ownership/Intellectual Property
- Protect Troops/Mission

We are concerned primarily with software-only means of protection

Underlying Goals

- Given the hardware/physical environment:

  make it hard for an adversary to reliably or predictably recover an intermediate or original form (Netlist, source level program code)

- Given recovery of some or all of the intermediate / original description of a circuit or program:

  make it hard for an adversary to recover, predict, subvert, or copy functionality

Ideal Software Protection…

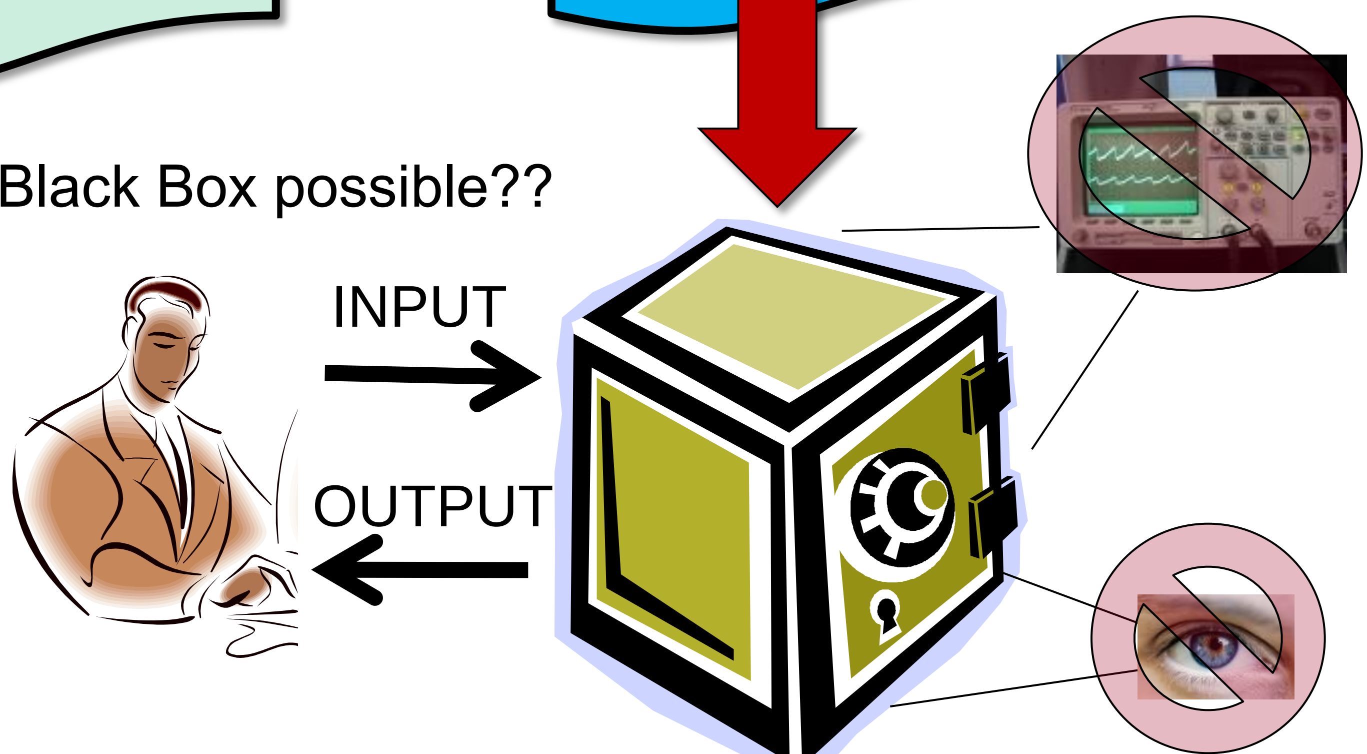
Program Source Code (Java/C++/C)

Circuit Netlist (VHDL/Verilog/BENCH)

Assembly

Realized Circuit/FPGA

Is a "Virtual" Black Box possible??



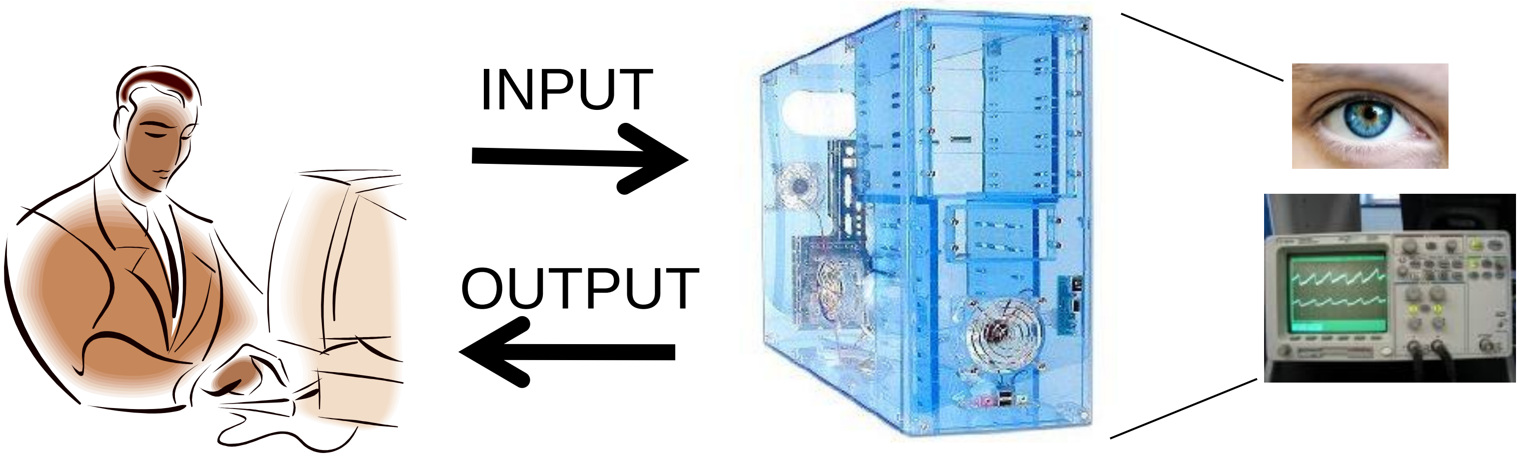
Real-world Software Protection…

Program Source Code (Java/C++/C)

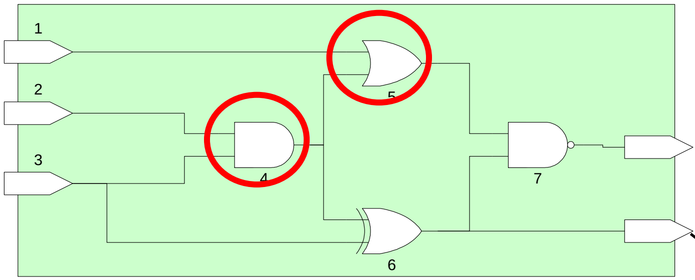
Circuit Netlist (VHDL/Verilog/BENCH)

Assembly

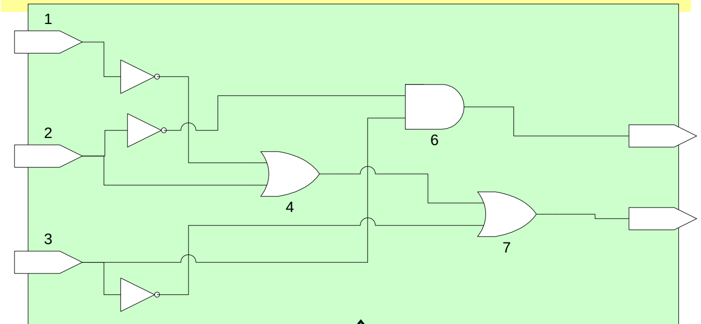
Realized Circuit/FPGA



General Intuition and Hardness of Obfuscation



The ONLY true "Virtual Black Box"



X1	X2	X3	4	5	Y6	Y7
			AND(3,2)	OR(4,1)	XOR(4,3)	NAND(5,6)
0	0	0	0	0	0	1
0	0	1	0	0	1	1
0	1	0	0	0	0	1
0	1	1	1	1	0	1
1	0	0	0	1	0	1
1	0	1	0	1	1	0
1	1	0	0	1	0	1
1	1	1	1	1	0	1

"The How"

X1	X2	X3	Y6	Y7
			XOR(4,3)	NAND(5,6)
0	0	0	0	1
0	0	1	1	1
0	1	0	0	1
0	1	1	0	1
1	0	0	0	1
1	0	1	1	0
1	1	0	0	1
1	1	1	0	1

Semantic Behavior

Program Understanding

- Adversary's ability to **anticipate a program's operational manifestation(s)**
- Adversary's ability to gain **intent indications** by **comparing** the obfuscated code, or segments, to **known code libraries**
- Adversary's knowledge gained relative to the theoretical **Virtual Black Box**
- Adversary's ability to extract the **information content** as manifested in the black box and white box aspects of program code

This is not the same as VBB or hiding all information…

Program Understanding

- **Our Context:** Prevent program understanding by limiting the amount of information gained by an adversary from either the blackbox or whitebox characteristics of a program/circuit
  - Programs are no more than **a special information class** with well-defined syntax and semantics
  - **Scrambling techniques are limited** because final form of program must adhere to rigid syntax and semantics
  - Program code **information content** is otherwise equivalent to information content in any other type of bit stream

- **Our Premise:** Program code that is statistically indistinguishable from a random bit stream has negligible information content

Defining Intent Protection

Is there an alternate (or better) way to measure security or protection?

Adversarial Observation:

Black Box Analysis

White Box Analysis

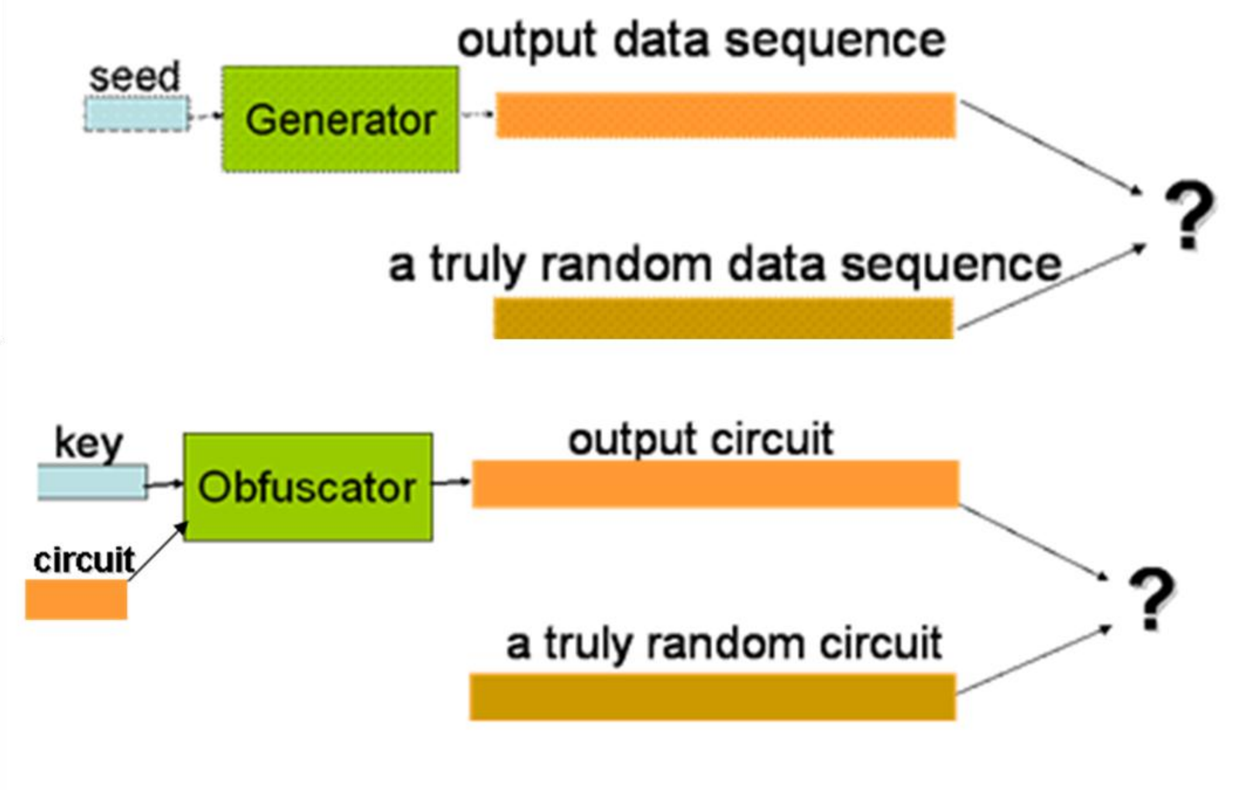
If the adversary cannot determine the function/intent of the device by input/ output analysis, we say it is black-box protected

If the adversary cannot determine the function/intent of the device by analyzing the structure of the code, we say it is white-box protected

Intent Protected: Combined black-box and white-box protection does not reveal the function/intent of the program

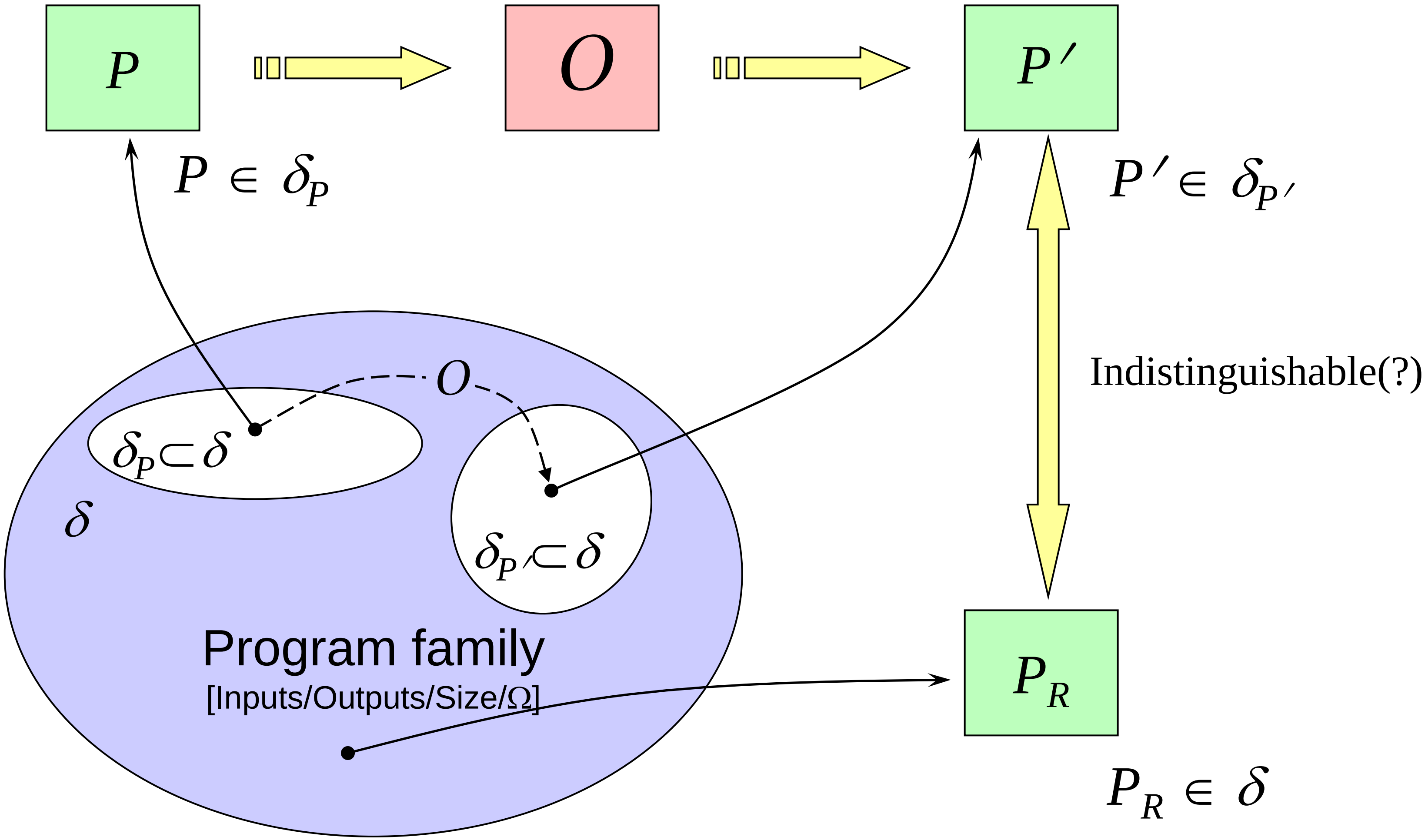
Random Programs/Circuits

Goals: Can we make **input/output** look random?
Can we make **structure** look random?



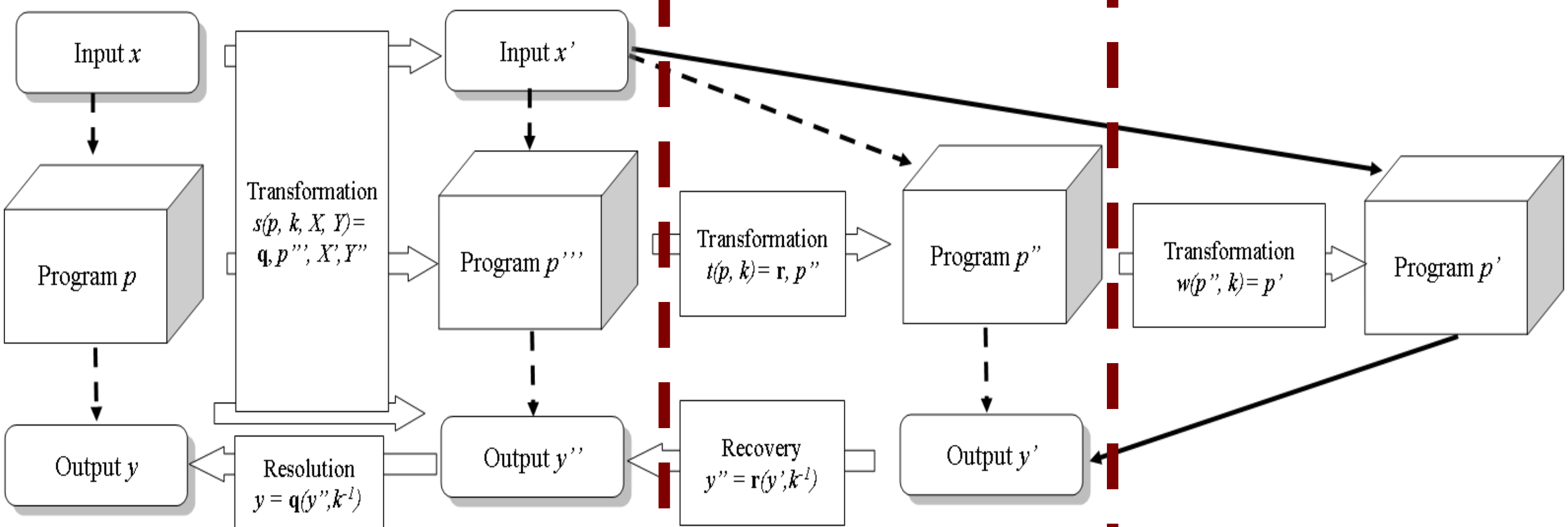
Instead of measuring security based on *leakage of information from the obfuscated program*, can we appeal to entropy or randomness as a measure for confusion in the obfuscated program?

RPM: Random Program Model



Combined Experimental Framework

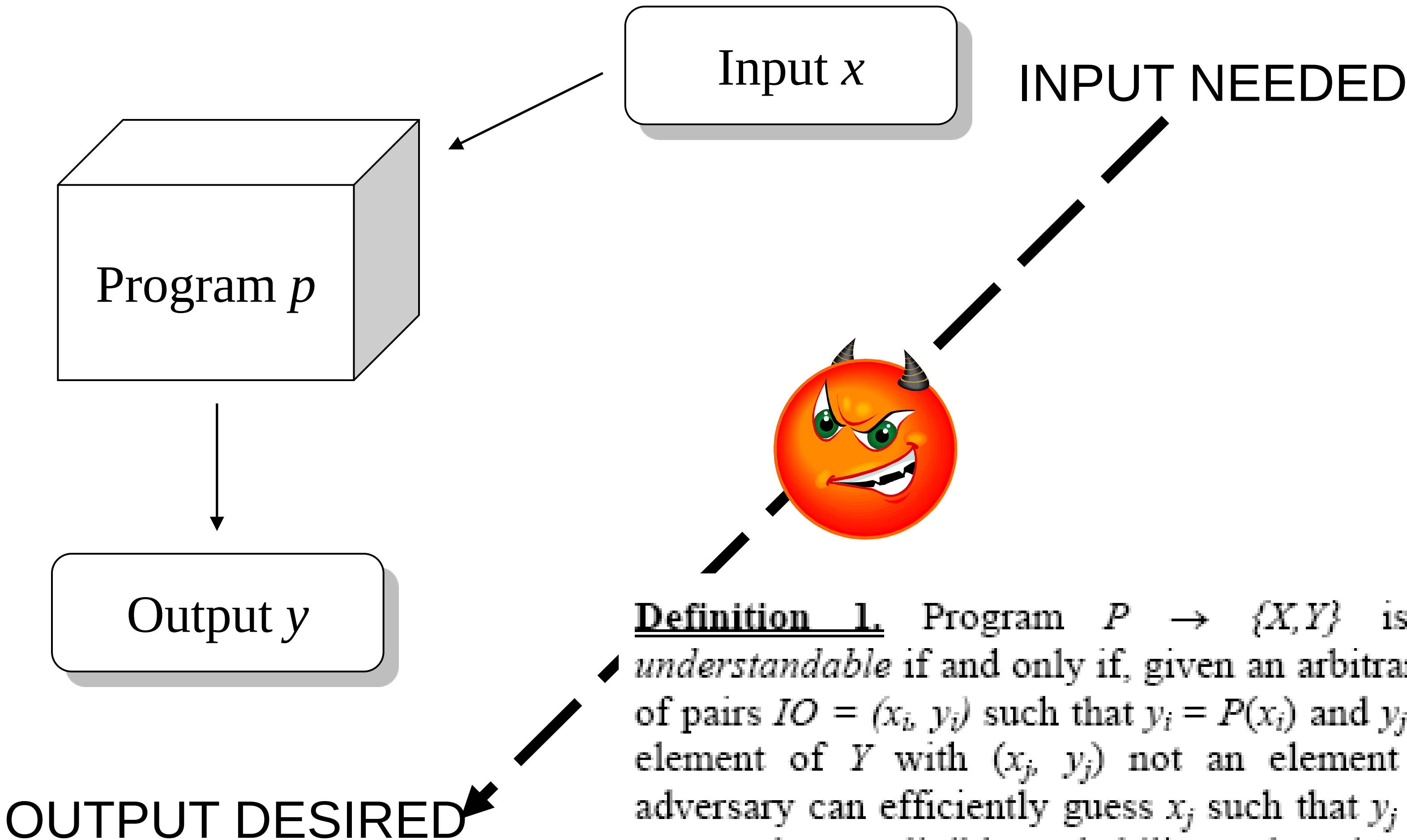
Black-box Refinement | **Semantic Transformation** | **White-box Randomization**



Black-Box I/O | **Black-Box I/O** | **White-Box Structure**

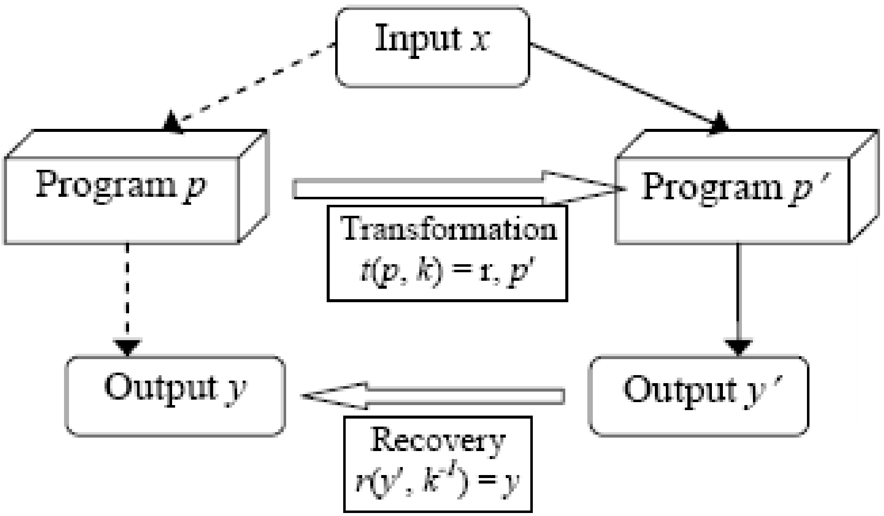
Goals: Can we make **input/output** look random?
Can we make **structure** look random?

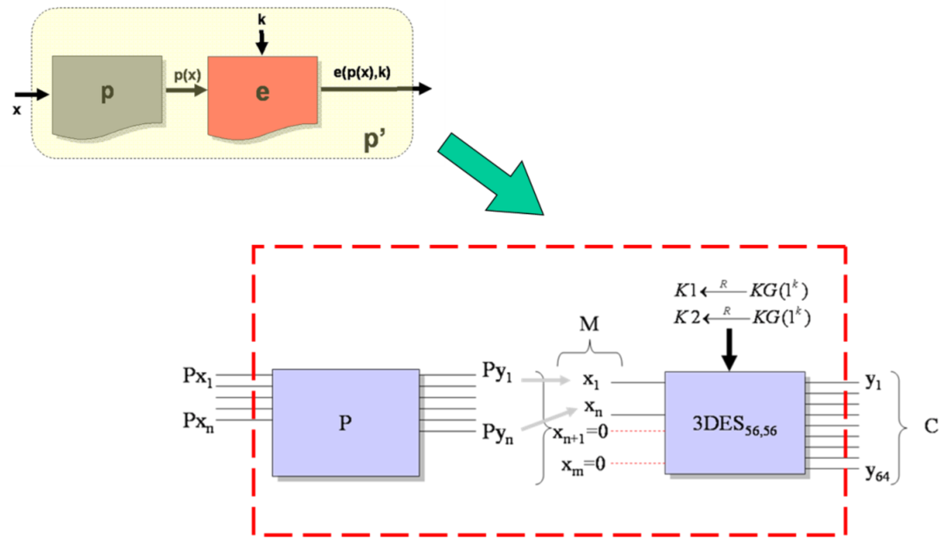
Protecting Black-Box Intent



Definition 1. Program $P \rightarrow \{X,Y\}$ is *black-box understandable* if and only if, given an arbitrarily large set of pairs $IO = (x_i, y_i)$ such that $y_i = P(x_i)$ and y_j an arbitrary element of Y with (x_j, y_j) not an element of IO), an adversary can efficiently guess x_j such that $y_j = P(x_j)$ with greater than negligible probability. Otherwise, we say P is *black-box obfuscated*.

Semantic Transformation

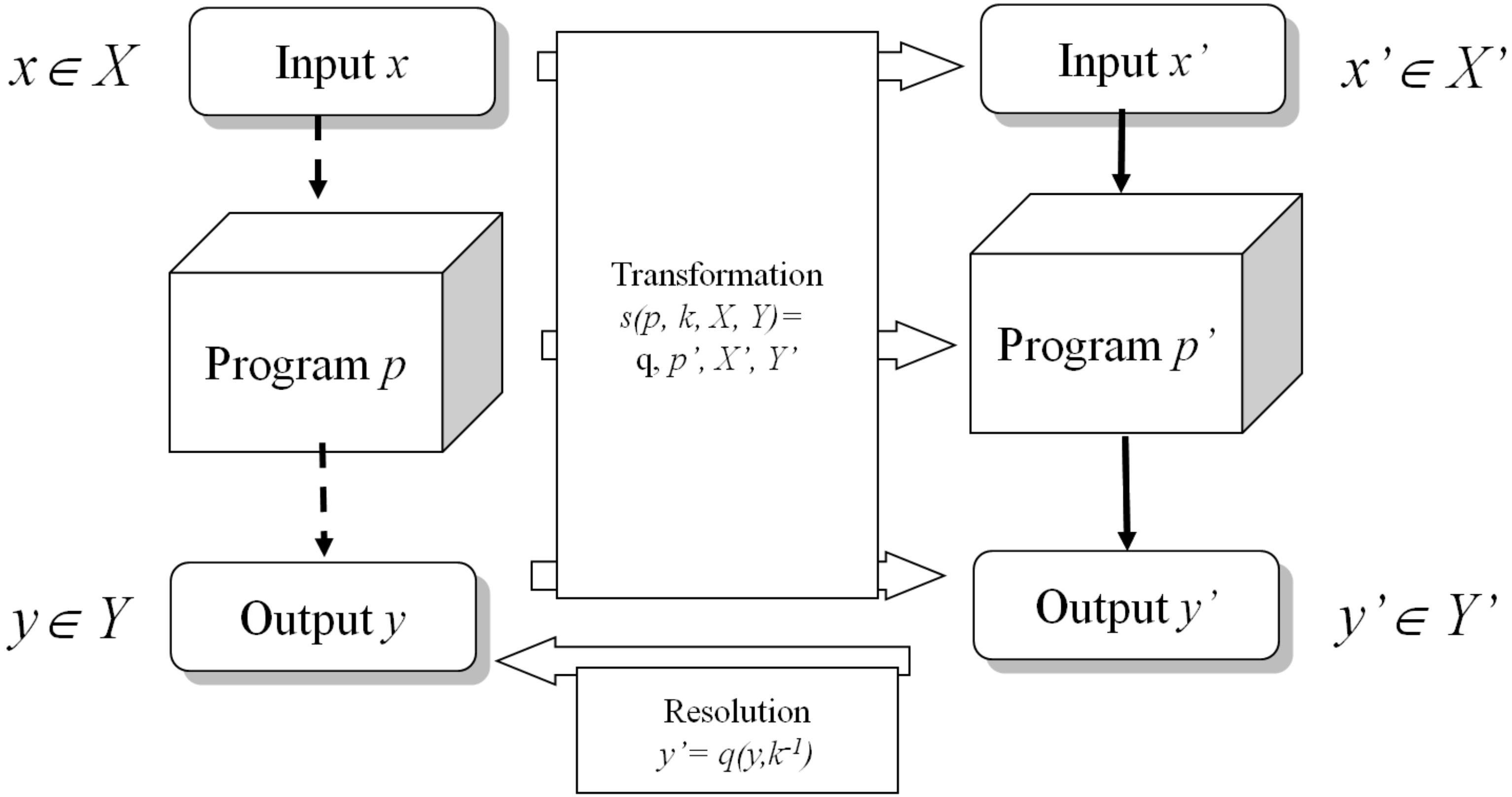




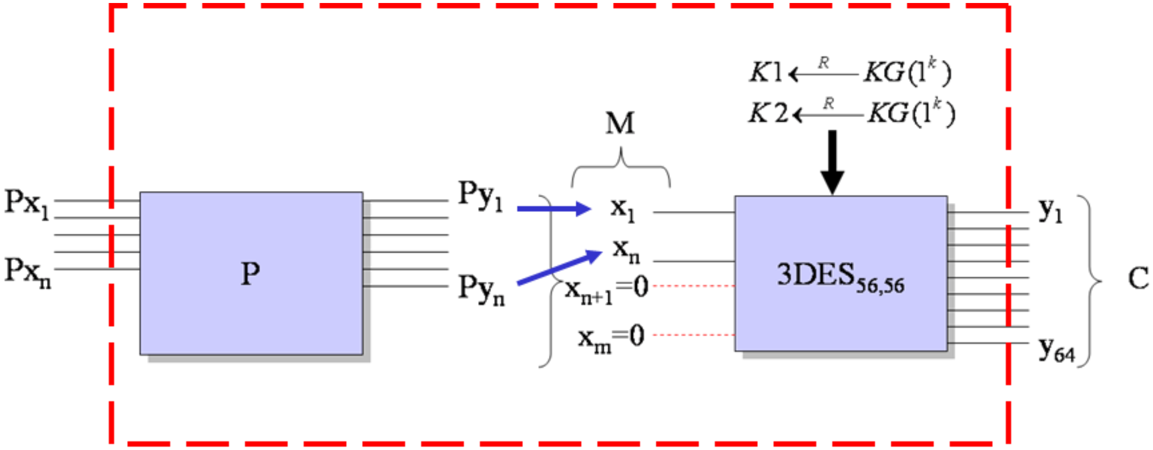
Semantically secure data encryption algorithms are black-box intent protected (BBIP)

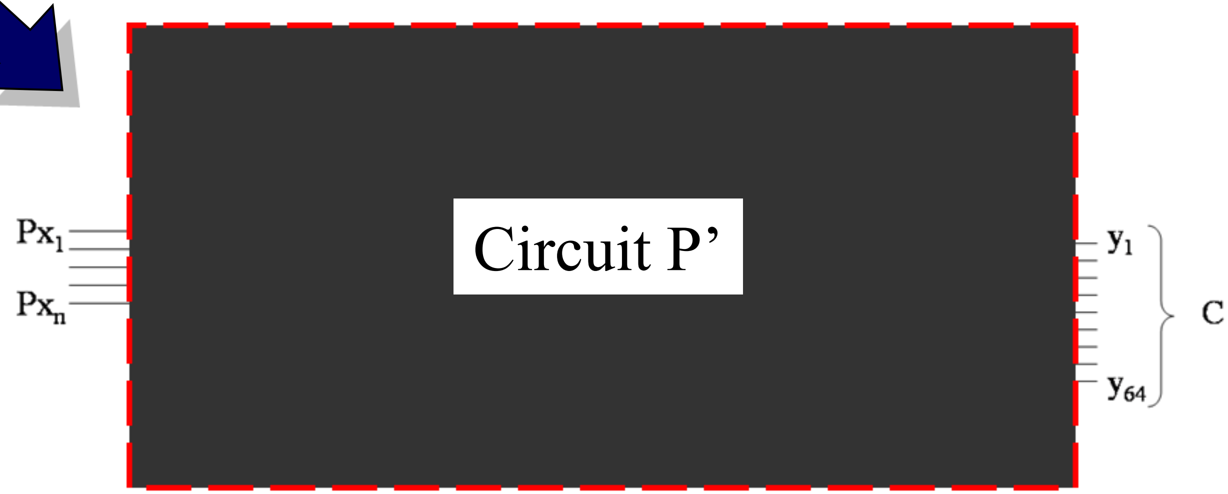
Compositions of programs with semantically strong algorithms are likewise BBIP

Black Box Refinement



Protecting White-Box Intent



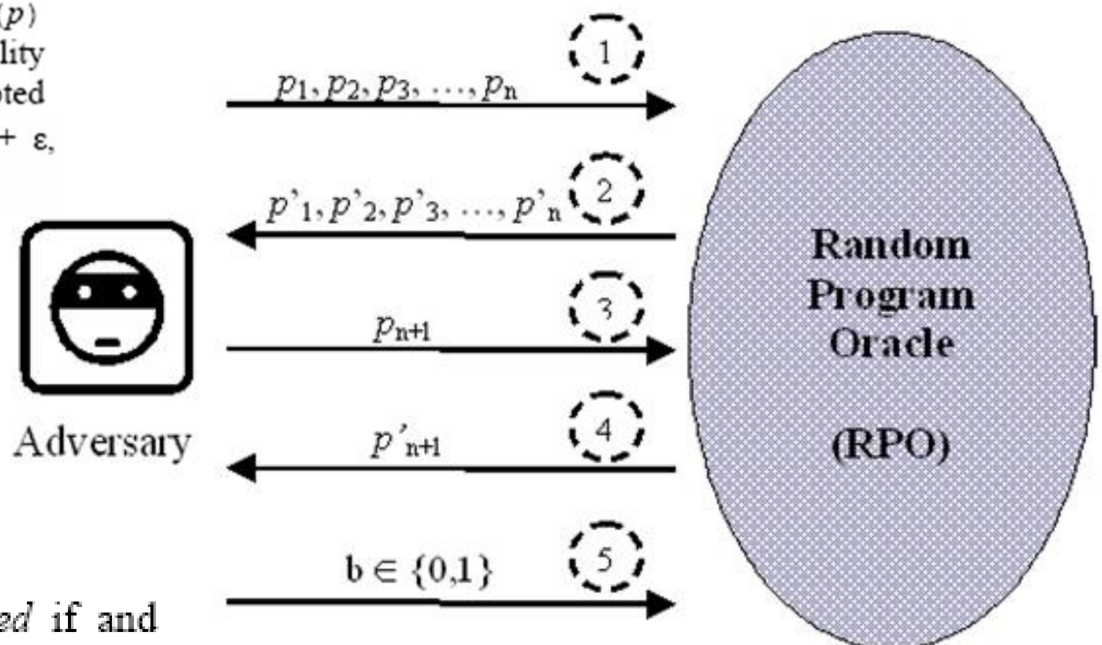


Ideal for AT applications where we shield hardware internals with some (reasonably) trusted AT method

Protecting White-Box Intent

Definition 2. Given access to a random program oracle which transforms any program p using algorithm $E(p)$ into an encrypted version p', and given full access to any encrypted program p'_x. After knowing any n pairs of original and encrypted programs $\{(p_1, p'_1), (p_2, p'_2), \ldots, (p_{n-1}, p'_{n-1}), (p_n, p'_n)\}$, an adversary that supplies a subsequent program p_{n+1} will receive p_{n+1}' from the oracle which is either: a random program (P_R) or the encrypted version of the program $p_{n+1}' = E(p_{n+1})$. The program $E(p)$ provides white-box protection if and only if the probability that an adversary is able to distinguish the encrypted program (p_{n+1}') from a random program (P_R) is ½ + ε, where ε is a negligible constant.

$$p_{n+1}' = \begin{cases} P_R & \Pr[p_{n+1}' = P_R] \leq \frac{1}{2} + \varepsilon \\ E(p_{n+1}) & \Pr[p_{n+1}' = E(p_{n+1})] \leq \frac{1}{2} + \varepsilon \end{cases}$$



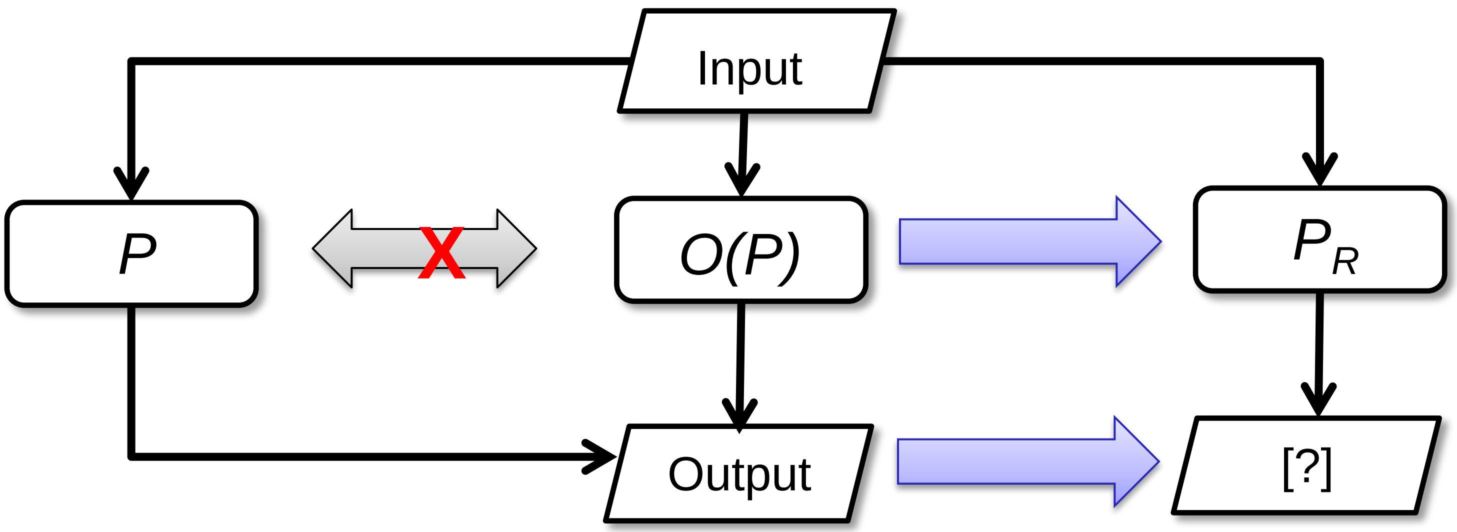
Definition 3. Program P is *intent protected* if and only if it is protected against black-box analysis and white box analysis.

Characterizing Intent Protection

- Conjecture when using Semantic Transformation:
  - If the output bits are predictable, then the output may be predictable
  - Treat each output position as a bit string generator
    - Run statistical randomness tests on each bit
- Questions of Interest to the Random Program Model:
  - **Does *structural* randomness produce *functional* randomness?**
    - Frequency of signature collisions (identical output patterns)
    - Approximate entropy of output bits
  - How random are the output bits?
    - Randomness values for specific statistical test

Methodology

- Unable to evaluate structure with agreed security metrics[1]
- Random Oracle used in absence of a defined security model
  - Sanity check for implementation
- Goal
  - O(P) structurally and functionally looks like P_R

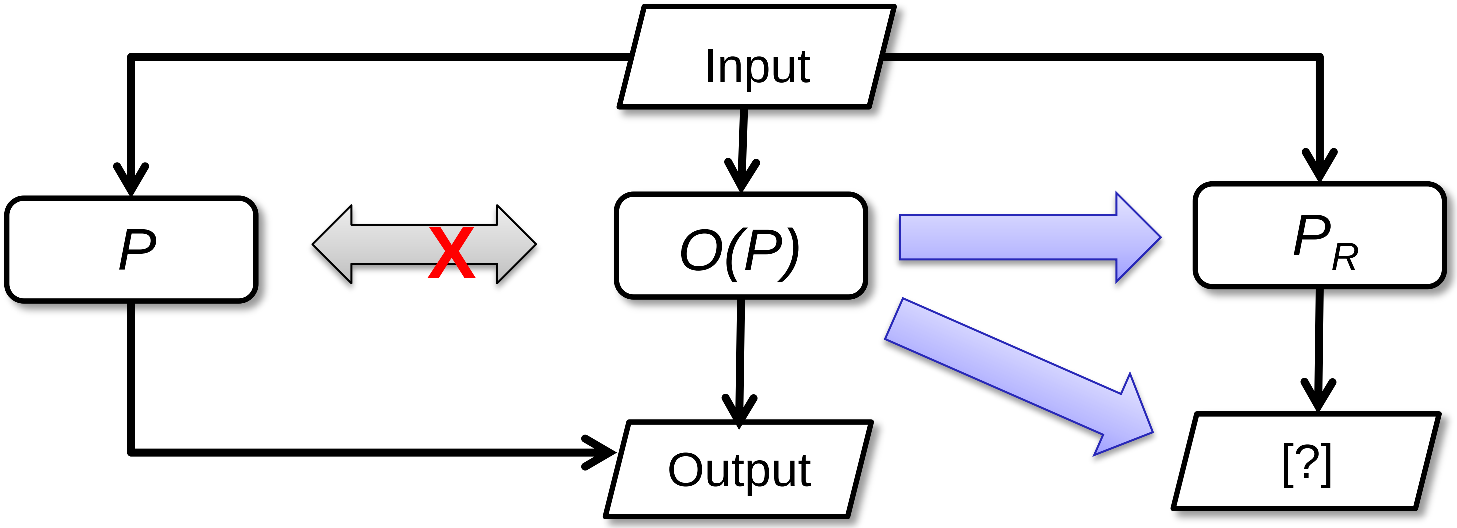


[1]National Institute of Standards and Technology

Experimental Design

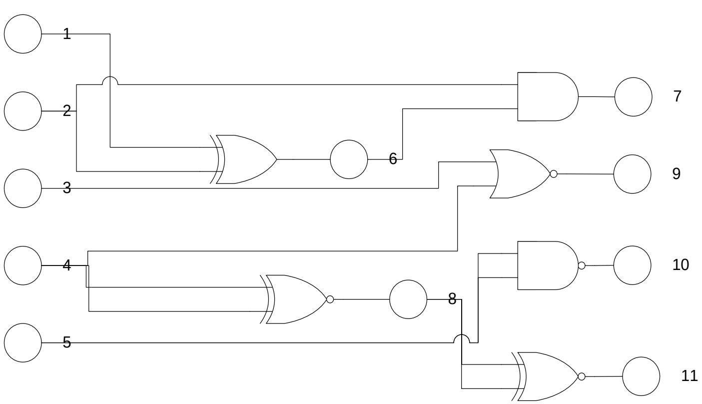
- Required components
  1. Design control /benchmark programs (deterministic)
  2. Generate P_R
  3. Black-box protect P

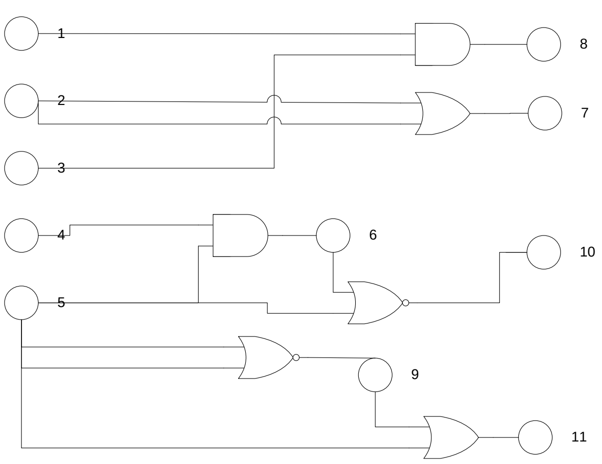
- Analysis
  - Compare P, black-box protected P, and P_R



Experimental Design

- Emulate deterministic functions w/combinational circuits
  - Abstracts high-level structure (ISCAS-85)
  - Build random circuits to analyze random circuit properties
  - Parameters (from benchmarks)
    - Input size (in bits)
    - Output size (in bits)
    - Number of intermediate nodes (represents structure)
    - Gate basis: AND, OR, XOR, NAND, NOR, NXOR





Experimental Design

- Goal
  - *O(P)* produces random functionality
- Add black-box protection to *P*
  - Weaken VBB function preservation
  - Strengthen overall security
    - Accounts for clean-room reverse engineering[1]
- Black-box w/ symmetric key cryptography
  - Produces blocks of pseudo-random bits
  - Pseudo-randomness measures exist[2]

Statistical tests
Frequency
Frequency Within a Block
Longest Runs of 1's in a Block
Runs of 0's and 1's
Cumulative Sum
Random Excursions
Random Excursions Variant
Approximate Entropy

[1]Schwartz "Reverse Engineering"

[2]National Institute of Standards and Technology

Experimental Design

- Configurations
  - Trusted-host output recovery
    - Secure execution on malicious host
    - Full structure; no functionality
  - Output recovery for malicious user
    - Partial execution on malicious host
    - Partial structure; full functionality
    - Loss of generality in function type (y = a * b + c)
  - Full ownership by malicious user/host
    - Secure structural *components*
    - Full structure; full functionality
    - Software Watermark
- Common design
  - Two-level structural configurations
    - Function Table (FT)
    - Boolean Equation Sets (BES)

x	y = f(x + x) y = f(2x) y = f(x << 1)
0	0
1	2
2	4
3	6
…	…
x_m	y_m

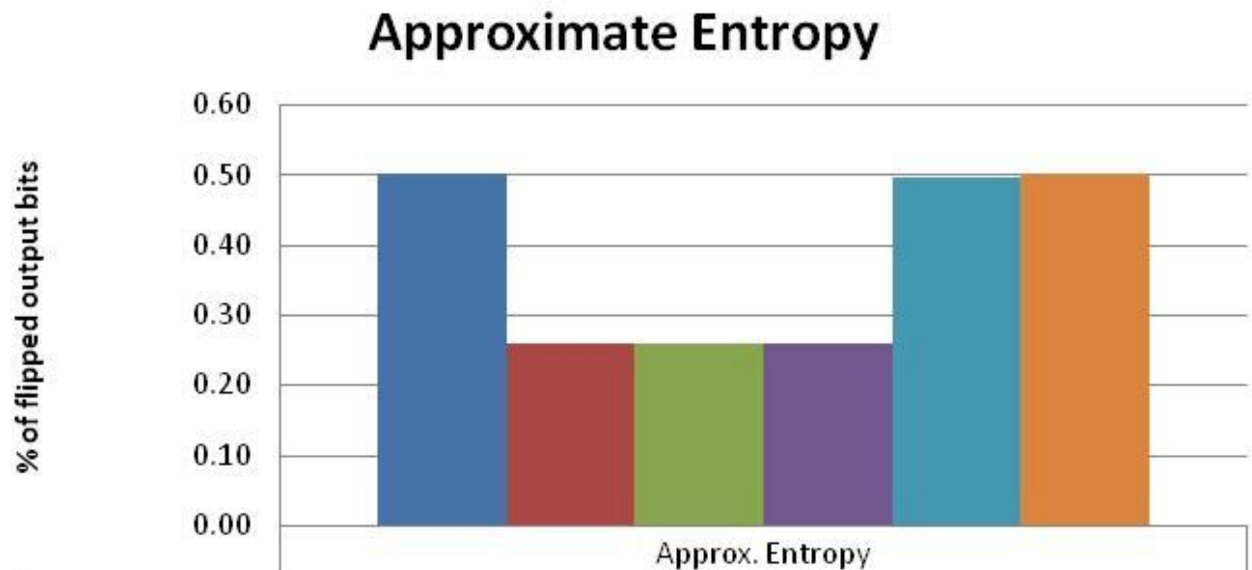
x	y = e(x, k)
0	66E94BD…89E0
1	58E2FCC…455A
2	F795AAA…C1E0
3	0388DAC…FE78
4	8ADE7D8…0291
5	95B84D1B…89E0
6	C94DA219…88F2
…	…
x_n	y_n

Experimental Design

- Complexity based brute-force attack on I/O size
  - Compute all function tables of size *m*-inputs, *n*-outputs
    - Super-exponential process, $O(m^n)$
  - Pair combinations of generated function tables in *m,n*
    - Factorial process, $O(n!)$
  - All operations of a lookup are the same
    - Index search, O(*1*) [or O(n) for BES]
    - No side-channel (performance/cost) leakage

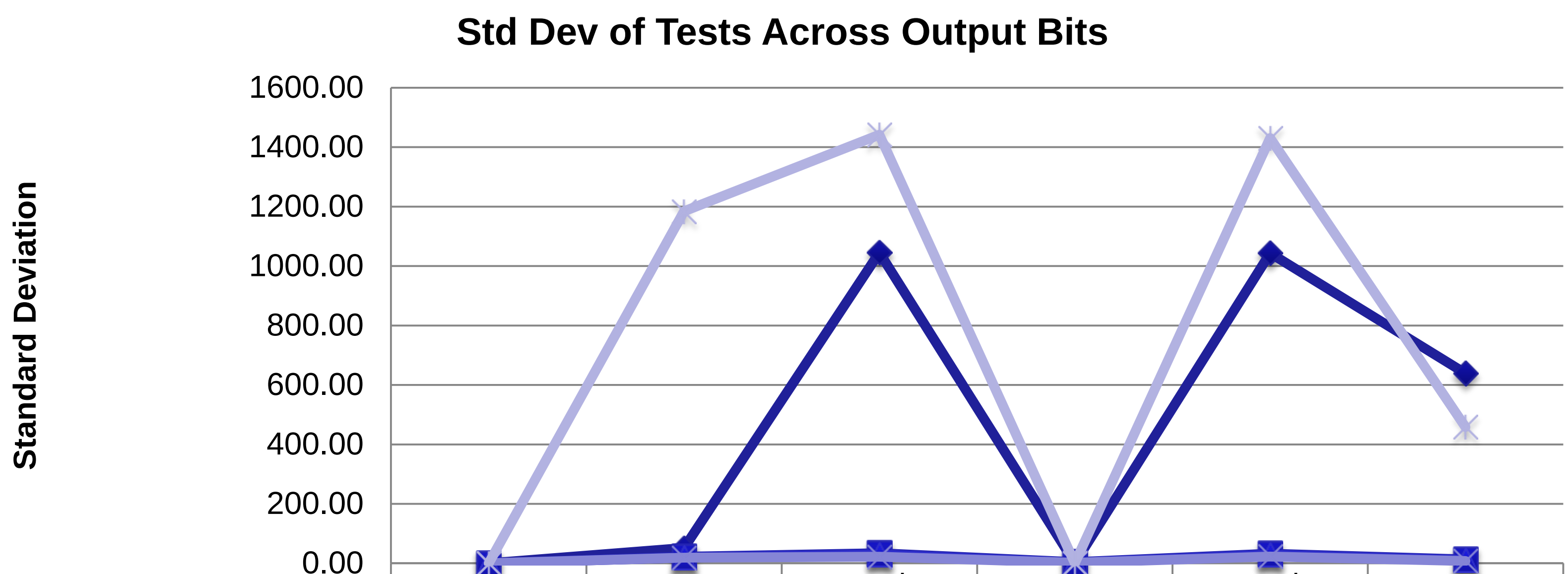
- Memory size
  - Function tables are at least (*n*-input) * (*m*-output) bits
  - Boolean equation sets are at least (*m-output) * p* terms
    - *m* equations stored in text form of *p* terms
    - Exponential size increase n^{pm}

Results and Analysis



	Approx. Entropy
AES	0.50
5-128-500 (GC)	0.26
5-128-1000 (GC)	0.26
c17 no pad	0.26
c17 CTR pad	0.50
c17 INPUT pad	0.50

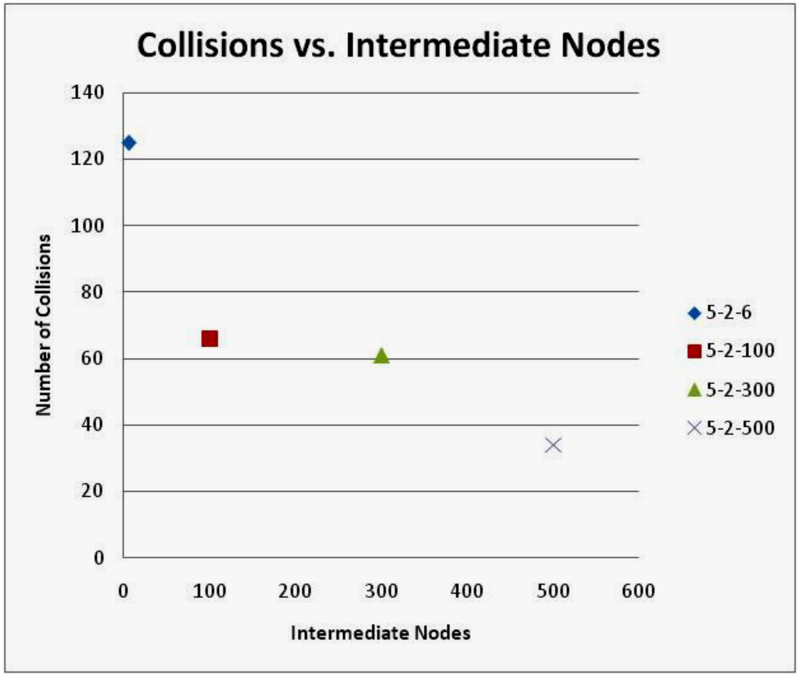
Results and Analysis

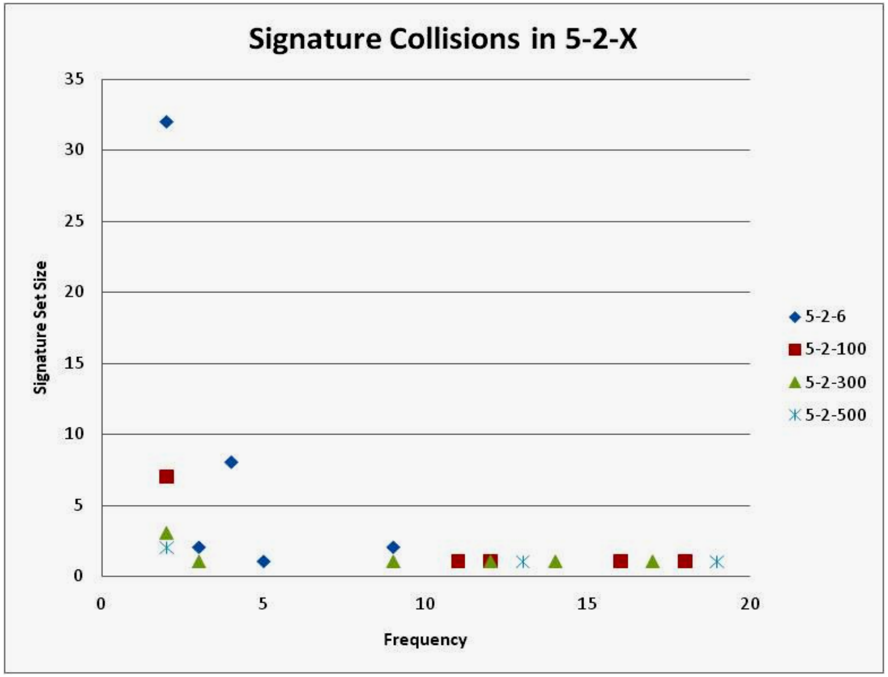


	% of 1's	Longest 1's Runs	Excursions from Zero	Zero Cycles	Excusion States	Runs of 1's
y = a * b + c (CTR)	0.12	51.47	1045.35	0.00	1043.59	639.31
12-8-100 (CTR)	0.01	22.18	33.75	4.18	32.45	13.27
12-8-300 (CTR)	0.01	19.05	28.94	1.77	28.56	10.42
12-8-500 (CTR)	0.01	19.06	22.27	1.66	22.72	7.94
12-8-100 (CTR) 0001	0.31	1184.28	1441.95	0.00	1430.44	458.58

Results and Analysis

- Possible signatures is (2^{output_bits}) ^ (2^{input_bits})
  - Collisions occur at ↑ frequency with ↓ intermediate node size
  - Collisions occur at ↑ concentration with ↑ intermediate node size





Conclusions

- Black-box metrics indicate bits where structural entropy is most needed if we keep function preservation property
  - Structural entropy may be insufficient depending on output pattern
  - Smaller circuits are better choices for random selection

- Enumeration is required—larger *n* requires greater resources upon generation, not execution
  - Advantage to developers with large computational resources
  - Reuse encryption function tables
  - Brute-force attack limited to adversaries with sufficient resources
  - Input/output size is easier to determine than function family

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Questions

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