Computationally Secure Information Flow

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Structure of the talk

- Background
  - What the problem is, how could we handle it.
- Problem statement
  - What to protect against, definitions.
- Our contribution
  - Program analysis for computationally secure information flow.
- Using a weaker cryptographic primitive
- Conclusions

Background

Programs may

- run in networked computers;
- access confidential data;
- communicate with other programs over the network.
  - some of them may be hostile.

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How can we find out, whether a program may leak confidential data?

- Cannot test for it.
  - One can test for properties of program runs.
  - Confidentiality — all program runs are similar.

Program Analysis

- Analyse the text of the program.
  - Try to prove that it preserves confidentiality.
- Try to automate the analysis.
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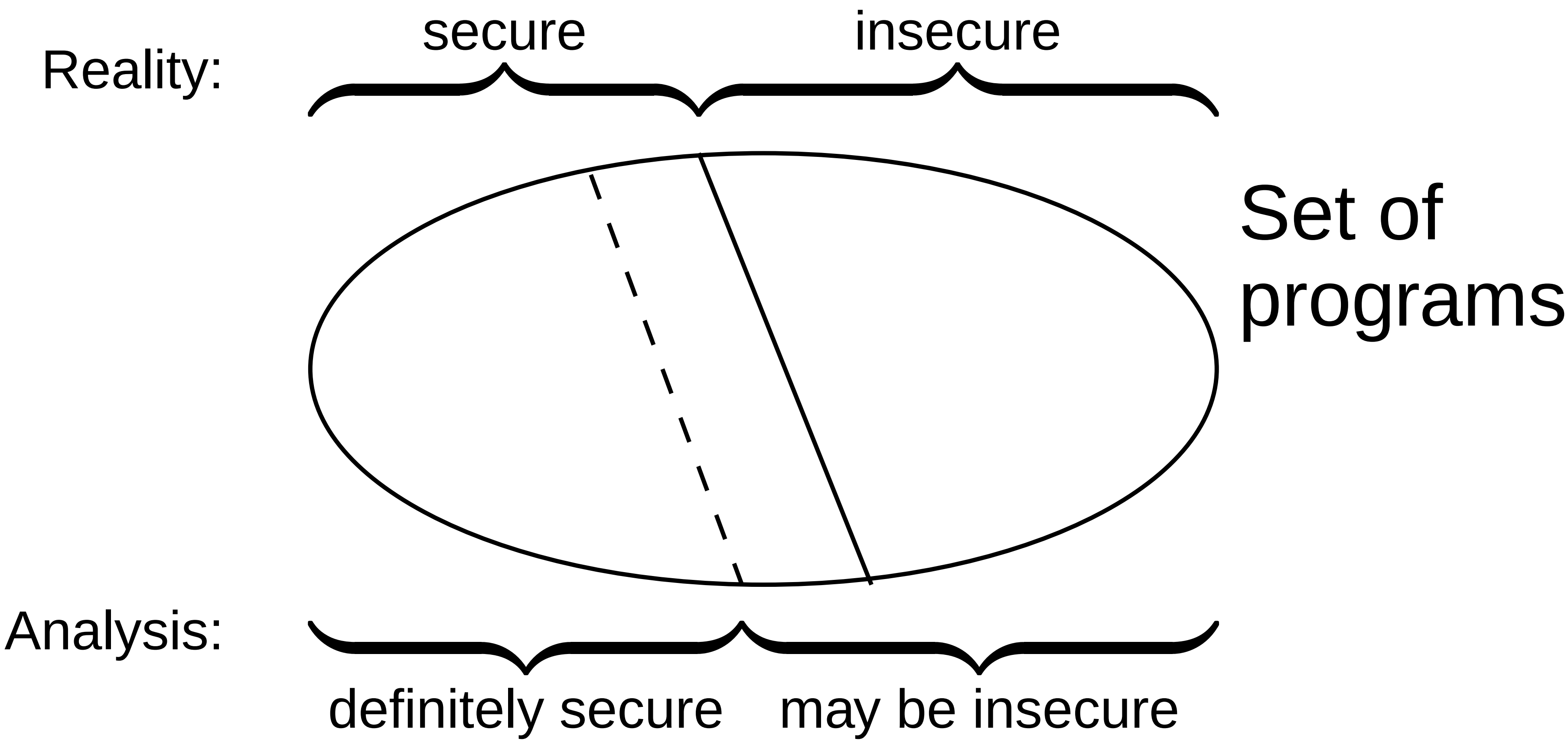
  - Try to prove that it preserves confidentiality.
- Try to automate the analysis.
- The question of preserving confidentiality is uncomputable.
- An automatic analysis must have
  - False positives — labeling a secure program insecure.
    - inconvinient, but causes no leaks.
  - False negatives — labeling an insecure program secure.
    - unsafe.

Program Analysis

Devise an analysis with no false negatives:



and with as few false positives as possible.

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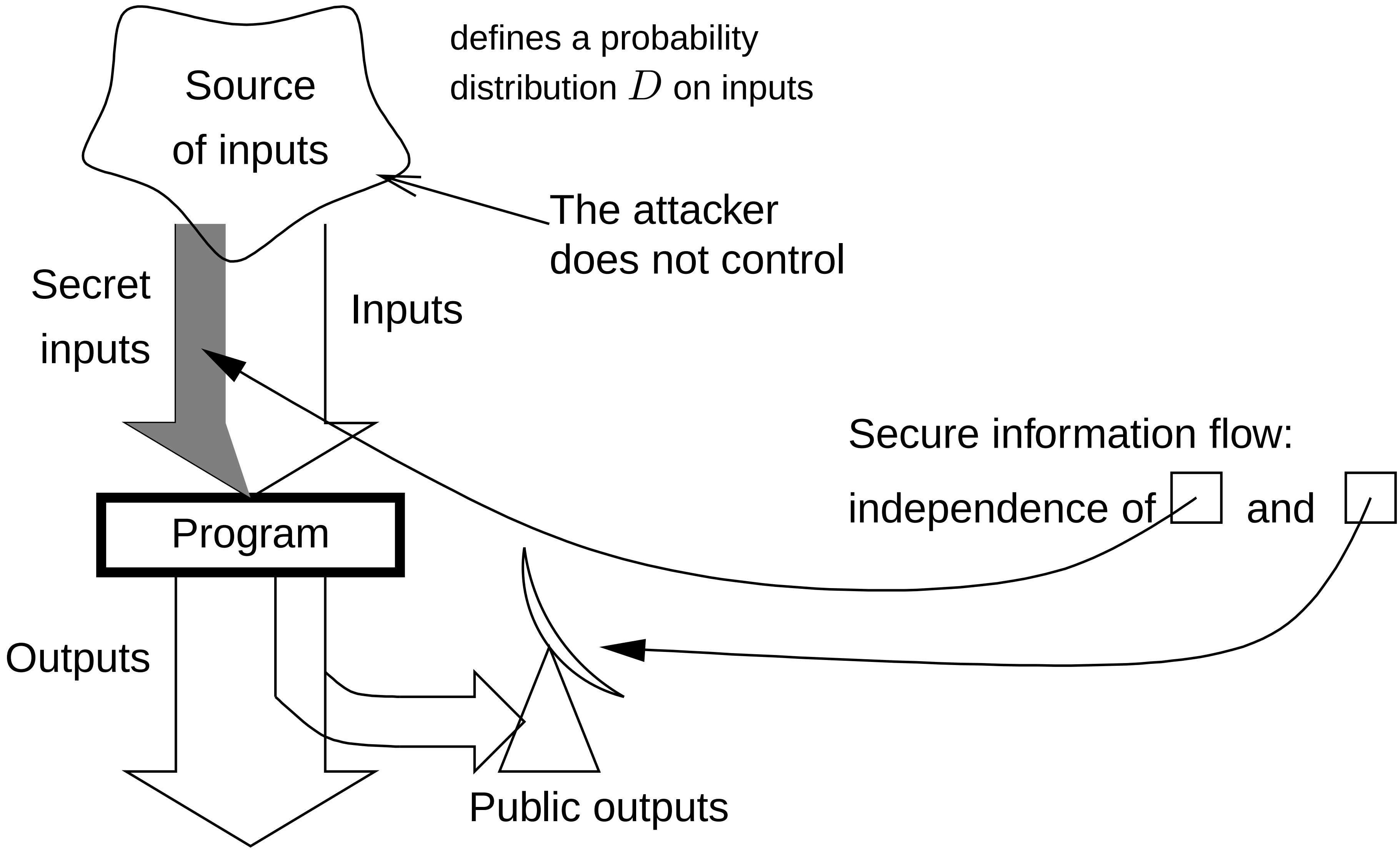
On the Attackers

- Some communication partners of the program are hostile.
  - What are their capabilities?
    - The security of the program depends on them.
- Two main categories of attackers:
  - Passive.
    - Can read from the network.
    - Cannot send any new data to the network.
  - Active.
    - Can read from the network.
    - Can also send data to the network.
- Active attackers are stronger than passive attackers.

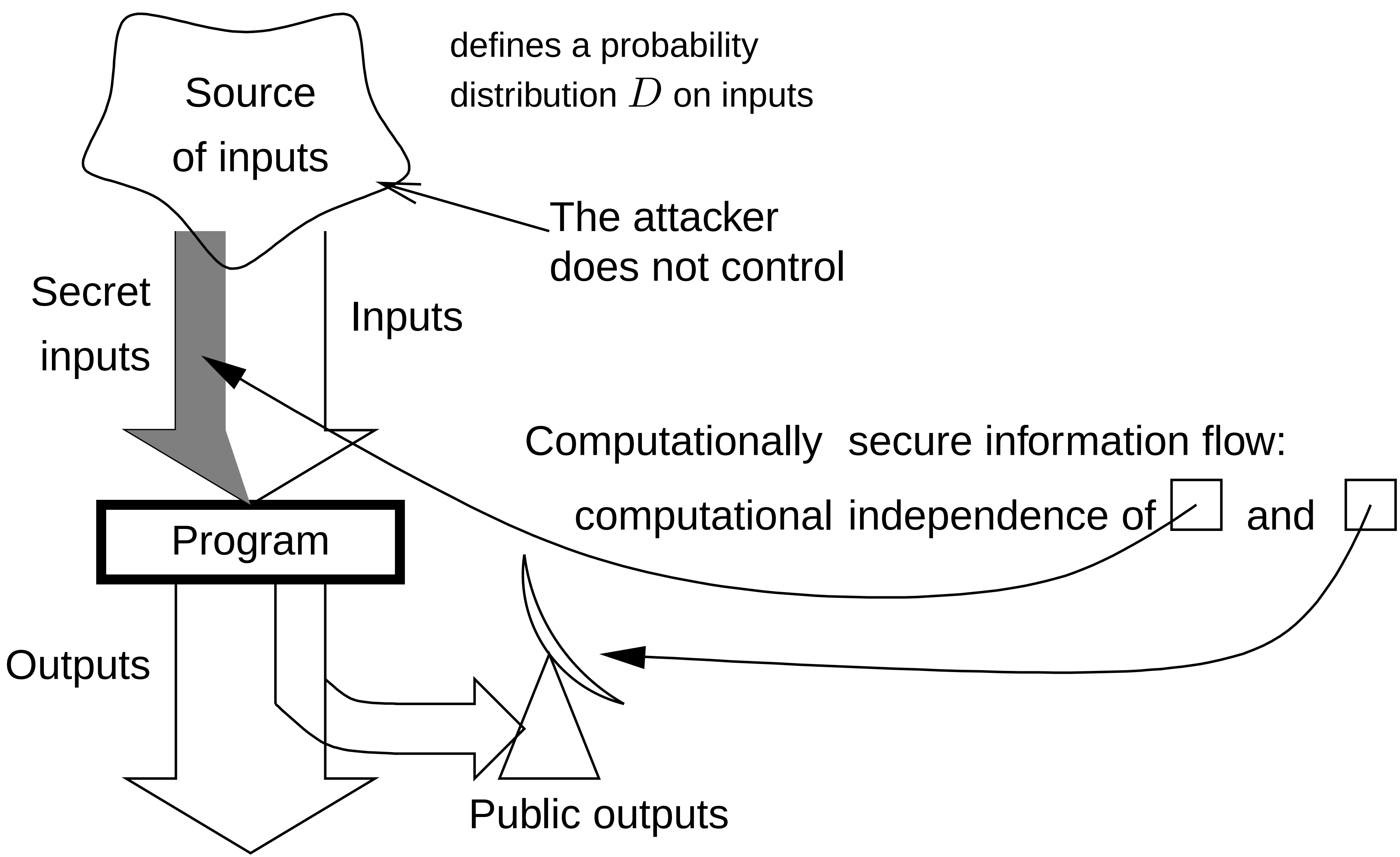
Only Passive Attackers

- We only consider security against passive attackers. In this case
  - The program has no dialogue with the environment.
  - The system may be modeled as follows:
    - The program is given its inputs. Some of the inputs are confidential.
    - The program processes the inputs and produces some outputs.
    - Some of these outputs are made public.
- This is the usual problem of secure information flow in programs.
- If we want to handle active attackers, we have to know, how to handle passive ones.

Illustration



Illustration



What do Compl.-Theor. Def.s Give?

- Allow to model cryptographic primitives more intuitively.
  - We use complexity-theoretic definitions of secure cryptographic primitives.
    - No efficient algorithm can *break* the primitive.
- For example — symmetric encryption: $x = \mathcal{E}_k(y)$
  - Information-theoretically: x is not independent of y.
    - At least when k is shorter than y.
  - Computationally: x is independent of y.
    - As long as y does not depend on k.

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Actually, the last condition is:

$$y \text{ is independent of} \longrightarrow \boxed{\mathcal{E}_k} \longrightarrow$$

Then also x is independent of $\longrightarrow \boxed{\mathcal{E}_k} \longrightarrow$.

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Our Contribution

- Definition of computationally secure information flow.
- Static program analysis for a simple imperative programming language.
  - Contains
    - assignments (with computations in RHS)
    - sequences of statements
    - *if-then-else*-branches
    - *while*-loops
  - The analysis handles symmetric encryption.
- Proof of correctness of the analysis.
  - Cannot use standard results about fix-point approximation.
- A practical implementation of the analysis.

Domain of the Analysis

- Given a program P, the analysis
  - Takes a description of the distribution of inputs.
  - Returns a description of the distribution of outputs.
- Description of distribution — set of pairs of variables (X, Y).
  - (Values of) variables in X are independent of variables in Y.
- Analysis is a function with domain and range $\mathcal{P}(\mathcal{P}(\mathbf{Var}) \times \mathcal{P}(\mathbf{Var}))$.

Domain of the Analysis

- Given a program P, the analysis
  - Takes a description of the distribution of inputs.
  - Returns a description of the distribution of outputs.
- Description of distribution — set of pairs of variables and encrypting black boxes (EBB) (X, Y).
  - (Values of) variables and EBBs in X are independent of variables and EBBs in Y.
- Analysis is a function with domain and range $\mathcal{P}(\mathcal{P}(\mathbf{Var} \uplus \mathbf{Var}) \times \mathcal{P}(\mathbf{Var} \uplus \mathbf{Var}))$.

Actually, we also have encrypting black boxes.

Base Step of the Analysis

- Consider the statement $x = o(x_1, \ldots, x_k)$
  - Let X be a set of variables and EBBs.
  - Suppose that $\{x_1, \ldots, x_k\}$ is independent of X before the statement.
  - Then x is independent of X after the statement.

Requirements for the Encryption

Encryption must hide the identities of plaintexts and keys:

- $\mathcal{E}$ must be *repetition-concealing*.
  - Let $x_1 = \mathcal{E}_k(y_1)$ and $x_2 = \mathcal{E}_k(y_2)$.
  - From x_1, x_2 impossible to find, whether $y_1 = y_2$.
  - For this, $\mathcal{E}_k$ must be probabilistic.

- $\mathcal{E}$ must be which-key concealing.
  - Let $x = \mathcal{E}_k(y)$ and $x' = \mathcal{E}_{k'}(y')$.
  - From x, x' impossible to find, whether $k = k'$.

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  - For this, $\mathcal{E}_k$ must be probabilistic.
  - A standard property.
- $\mathcal{E}$ must be which-key concealing.
  - Let $x = \mathcal{E}_k(y)$ and $x' = \mathcal{E}_{k'}(y')$.
  - From x, x' impossible to find, whether $k = k'$.
  - A nonstandard property.
  - Some standard constructions achieve it.

Analysing the Encryption

- Consider the statement $x = \mathcal{E}_k(y)$
  - Let X be a set of variables and EBBs.
  - Suppose that $\boxed{\mathcal{E}_k}$ is independent of $X \cup \{y\}$ before the statement.
    - Note that y may be dependent of X.
  - Then x is independent of X after the statement.
- Consider the statement $k = Generate\_Key()$
  - Then $\boxed{\mathcal{E}_k}$ is independent of $\boxed{\mathcal{E}_k}$ after the statement.

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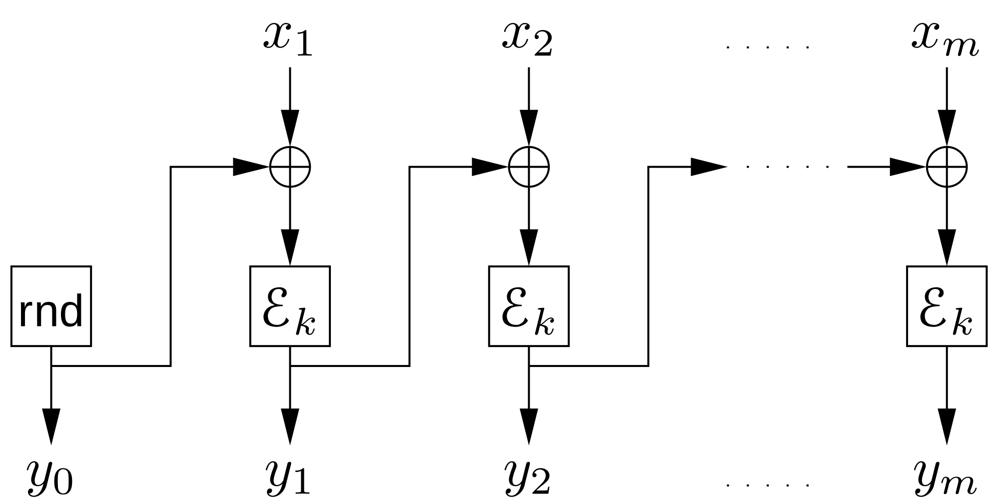
More Primitive Encryption

- Which-key and repetition concealing encryption primitives are usually constructed from more primitive operations.
- These operations are assumed to be *pseudorandom permutations* (PRP).
- Directly handling pseudorandom permutations may help efficiency.



Our Contribution

- Analysis for secure information flow for programs without loops.
  - The encryption is assumed to be a PRP.
- Additionally: means for checking, whether the outputs of two programs have “the same” distribution.
  - For comparing our results with earlier ones.
- We can automatically deduce the security of some block-ciphers’ modes of operation.

Earlier work

- Programs without loops
- Which-key and repetition concealing encryption
- Cannot analyse *encryption cycles*

$$\mathcal{E}_{k_1}(k_2), \mathcal{E}_{k_2}(k_3), \ldots, \mathcal{E}_{k_{n-1}}(k_n), \mathcal{E}_{k_n}(k_1)$$

  - Neither can we, when analysing PRPs.

Conclusions

In this thesis we

- gave an analysis for secure information flow, which can analyse encryption operations;
- showed that this analysis can be implemented efficiently;
- (probably) started the study of automated reasoning about systems containing pseudorandom permutations.