

Advanced Cryptography

1st Semester 2007-2008

Introduction

Pascal Lafourcade

Université Joseph Fourier, Verimag

Master 2 Pro: September 20th 2007

Instructors

Instructors

- Pascal Lafourcade: pascal.lafourcade@imag.fr
- Jean-Louis Roch: jean-louis.roch@imag.fr
- Florent Autreau: florent.autreau@imag.fr

Administrative Informations

Where & When

- Module of 20 sessions Weeks 38-48:
 - 8 sessions with JL Roch Weeks 38-46
 - 8 sessions with P Lafourcade Weeks 38-46
 - 4 sessions with F Autreau Weeks 37-48

Holidays & Exams

- Holidays: Week 44
- Exam: Week 49
- Evaluation:
 - 1 final exam (3 hours, 4 ECTS, i.e. 66% of the final mark)
 - 1 project lab with homework (2 ECTS, 33% of the final mark)

Organization

Timetable and Rooms

- Monday 8.00 am - 10.00 am Room H203 and H105
- Thursday 8.00 am - 10.00 am Room H104
- Thursday 10.15 am - 11.15 am Room H104 (English)
- Thursday 10.15 am - 11.15 am Room H102 (French)

Is it fair? what do you prefer, suggest?

Twice Thursday with me and after Monday.

During each lecture, two students will take some notes, and produce a latex file for the next week.

Instructor Information (I)

Address

- Instructor: Pascal Lafourcade
- Address:

VERIMAG, team DCS
Center Equation CTL
2, avenue de Vignate
38610 Gières

- Office: B4D CTL 1st floor
- Email: pascal.lafourcade@imag.fr
- Web: <http://www-verimag.imag.fr/~plafourc/>
- Phone: +33 (0) 4 56 52 04 21 (but email is better)
- Available most of the time in my office by appointment

Instructor Information (II)

Research in:

Information Security, Formal Verification, Cryptographic Protocols, Rewriting, Unification, Equational Theories, Constraints:

- e-voting
- e-auction
- Group protocols
- Wireless communications
- Tools
- ...

Web Pages

Courses Web Pages:

- Practical Informations online.
- Slides, homeworks, references, articles...

Unit part:

http://www-id.imag.fr/Laboratoire/Membres/Roch_Jean-Louis/perso_html/COURS/KIOSK-SCCI-SecurityModels//

My part:

www-verimag.imag.fr/~plafourc/teaching/Master_Pro_2_2007_2008.php

What about YOU?

Please fill the form.

Prerequisites

Some familiarity with computer system:

- operating systems,
- networks,
- programming languages.

Some mathematical notions:

- a little number theory,
- some probability notions,
- ability to follow and do proofs,
e.g., proof by induction, contradiction...
- acquaintance with logic,
- ease with formal notation and manipulation,

but no advanced mathematics required.

Please see me if you have any doubt or question.

What is this course about?

A Master 2nd year course.

A presentation to basics and essential notions, techniques, models used in security and cryptography.

A look at some more advanced topics in cryptography, in particular topics related to the link between mathematical point of view and computer science one.

Course topics, in details

- Introduction
- Indistinguishability
- Public Encryption
- Symmetric encryption
- Security protocols:
 - Symbolic Model
 - Computational Model
- Non-interference Problem
- Access Control and Security Policies
- And a little more, if possible...

Today: Introduction.

Contents (I)

Security touches many domains:

- cryptography,
- mathematics,
- operating system,
- networking,
- economics,
- policy and law ...

We should at least touch most of these topics, but we will not try to cover all aspects of security.

Contents (II)

- Not a course on cryptography,
- Not a complete course on security.

Reading

Required reading:

- No textbook!
- Many papers, indicated during the course.

Some recommended book:

- Two volumes of:
“The Foundations of Cryptography” by Oded Goldreich
- For background on cryptography, online book:
“The handbook of applied cryptography” by Alfred J. Menezes, Paul C. van Oorschot and Scott A. Vanstone.
www.cacr.math.uwaterloo.ca/hac/index.html

More books

- Bruce Schneier “Applied cryptography” ,
- Matt Bishop “Computer Security: Art and Science” ,
- Douglas Stinson “Cryptography: Theory and Practice” ,
- Simon Singh “The Code Book: The Secret History of Codes and Code Breaking” .

Course work

- Reading.
- Class participation.
- Homework:
 - Given and explained in class,
 - Given in the slides,
 - Usually due at the start of class one week later.
 - Latex file summarizing previous lecture.
- Exam.

Cheating (I)

- All work you make must be your own!
- If you do not know if something is allowed, please ask.
- Cheating will result in failure of the course and other standard measures.

Regular class attendance is required!

Cheating (II)

- You are encouraged to discuss the course material and assignments with others.
- You are not allowed to do assignments with others
- You may use any conversations, texts, or other material, as long as you cite your sources.

Outline

- 1 Presentation
- 2 Motivations
- 3 Probabilities
 - Mathematics Recalls
 - Definitions
 - Birthday Paradox
- 4 Perfect Encryption

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Typical security-critical problems

- Secure communication, e.g., via telephone, email, fax.
Objective: confidentiality and integrity of transmitted information.
- Internet banking. **Objectives:** confidentiality of transactions and account information, prevention of false transactions, impossibility of repudiating (denying) a transaction by a user,
...
- Digital payment systems.
- E-voting systems.
- Digital rights management.

N.B.: specifying objectives (security properties) is not always easy.
Neither is building systems that satisfy these objectives!

Traditional security properties

- Policies are often formulated to achieve certain standard security properties (also called security goals)
- Common security properties are:
 - Confidentiality or Secrecy: No improper disclosure of information
 - Integrity: No improper modification of information
 - Availability: No improper impairment of functionality/service
- Note that: (Im)proper must be specified individually, for each system.

Other security properties

- **Authenticity** (e.g., “channel input only accessible to sender”) is often the same as integrity, with just a difference of emphasis.
- **Non-repudiation** (also called **accountability**) is where one can establish responsibility for actions.
- **Plausible deniability** is contrary to non-repudiation and can be seen as weak form of secrecy.
- **Privacy**
 - **Anonymity**: secrecy of principal identities or communication relationships.
 - **Pseudonymity**: anonymity plus link-ability.
 - **Data protection**: personal data is only used in certain ways.

Example: banking

- A bank may require
 - authenticity of clients (at teller, ATMs, or on the Internet),
 - non-repudiation of transactions,
 - integrity of accounts and other customer data,
 - secrecy of customer data, and
 - availability of logging.
- The conjunction of these properties might constitute the bank's (high-level) security policy.

Another example: e-voting

- An e-voting system should ensure that
 - only registered voters vote,
 - each voter can only vote once,
 - integrity of votes,
 - privacy of voting information (only used for tallying), and
 - availability of system during voting period
- In practice, many policy aspects are difficult to formulate precisely.

Exercise: Give the security properties that an international airport should guarantee.

More details with Florent Autreau later.

Outline

1 Presentation

2 Motivations

3 Probabilities

Mathematics Recalls

Definitions

Birthday Paradox

4 Perfect Encryption

Probability Distribution (I)

A **finite probability distribution** $D = (U, P)$ is a finite, non-empty set U , together with a function P that maps $u \in U$ to $P[u] \in [0, 1]$, such that

$$\sum_{u \in U} P[u] = 1$$

The set U is called the **sample space** and the function P is called the **probability function**.

Example

If we think of rolling a fair die, then $U := \{1, 2, 3, 4, 5, 6\}$, and $P[u] := 1/6$ for all $u \in U$ gives a probability distribution describing the possible outcomes of the experiment.

Probability Distribution (II)

An event is a subset A of U , and the probability of A is:

$$P[A] := \sum_{u \in A} P[u]$$

Properties

For an event $A \subseteq U$, let \bar{A} denote the **complement** of A in U .

$$P[\emptyset] = 0, P[U] = 1, P[\bar{A}] = 1 - P[A]$$

For any events $A, B \subseteq U$, if $A \subseteq B$, then $P[A] \leq P[B]$. Also, for any events $A, B \subseteq U$, we have

$$P[A \cup B] = P[A] + P[B] - P[A \cap B] \leq P[A] + P[B]$$

in particular, if A and B are disjoint, then $P[A \cap B] = 0$ and $P[A \cup B] = P[A] + P[B]$.

Probability Distribution (III)

More generally, for any events $A_1, \dots, A_n \subseteq U$ we have

$$P[A_1 \cup \dots \cup A_n] \leq P[A_1] + \dots + P[A_n]$$

and if the A_i are pairwise disjoint, then

$$P[A_1 \cup \dots \cup A_n] = P[A_1] + \dots + P[A_n]$$

DeMorgan's law

Let A and B two events, we have:

- $\overline{A \cup B} = \bar{A} \cap \bar{B}$
- $\overline{A \cap B} = \bar{A} \cup \bar{B}$

Distributive law

For events A, B, C , we have:

- $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$
- $A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$

Conditional distribution

Let $D = (U, P)$ be a probability distribution. For any event $B \subseteq U$ with $P[B] \neq 0$ and any $u \in U$, let us define:

$$P[u|B] := \begin{cases} \frac{P[u]}{P[B]} & \text{if } u \in B, \\ 0 & \text{otherwise} \end{cases}$$

For any event $A \subseteq U$, we have

$$P[A|B] = \sum_{u \in A} P[u|B] = \frac{P[A \cap B]}{P[B]}$$

value $P[A|B]$ is called the **conditional probability** of A given B .

Random variables (I)

Let $D = (U, P)$ be a probability distribution. A **random variable** X is a function from U into a set \mathcal{X} . If \mathcal{X} is a subset of the real numbers, then X is called a **real random variable**:

$$X(U) = \{X(u) : u \in U\}.$$

Properties

If $X : U \rightarrow \mathcal{X}$ is a random variable, and $f : \mathcal{X} \rightarrow Y$ is a function, then $f(X) := f \circ X$ is also a random variable.

Let $X : U \rightarrow X$ be a random variable. For $x \in \mathcal{X}$, we write " $X = x$ " as shorthand for the event $\{u \in U : X(u) = x\}$.

Random variables (II)

A random variable X defines a probability distribution on its image \mathcal{X} , where the probability associated with $x \in \mathcal{X}$ is $P[X = x]$. We call this the **distribution** of X .

Two random variables X, Y defined on a probability distribution, $Z := (X, Y)$ is also a random variable whose distribution is called the **joint distribution** of X and Y .

Two random variables X, Y are **independent** if for all x in the image of X and all y in the image of Y , the events $X = x$ and $Y = y$ are independent:

$$P[X = x \wedge Y = y] = P[X = x]P[Y = y]$$

Theorem: Bayes

Suppose we have a collection B_1, \dots, B_n of events that partitions U , such that each event B_i occurs with non-zero probability. Then it is easy to see that for any event A ,

$$P[A] = \sum_{i=1}^n P[A \cap B_i] = \sum_{i=1}^n P[A|B_i]P[B_i]$$

Furthermore, if $P[A] \neq 0$, then for any $j = 1, \dots, n$, we have:

$$P[B_j|A] = \frac{P[A \cap B_j]}{P[A]} = \frac{P[A|B_j]P[B_j]}{\sum_{i=1}^n P[A|B_i]P[B_i]}$$

This equality, known as Bayes' theorem, lets us compute the conditional probability $P[B_j|A]$ in terms of the conditional probabilities $P[A|B_i]$.

Exercise: Proofs already done by Jean-Louis.

Bayes Example: Cookies

	Bowl 1	Bowl 2	Totals
Chocolate Chip	10	20	30
Plain	30	20	50
Total	40	40	80

Figure: Number of cookies in each bowl by type of cookie

Fred picks a bowl at random, and then picks a cookie at random.

The cookie turns out to be a plain one. How probable is it that Fred picked it out of bowl 1?

What is the probability that Fred picked bowl 1, given that he has a plain cookie?

Cookies Answer (I)

	Bowl 1	Bowl 2	Totals
Chocolate Chip	1/8	1/4	3/8
Plain	3/8	1/4	5/8
Total	1/2	1/2	1

Figure: Relative frequency of cookies in each bowl by type of cookie

- $Pr(A)$ = the probability that Fred picked bowl 1 regardless of any other information. Hence $Pr(A) = 1/2$
- $Pr(B)$ = the probability of getting a plain cookie regardless of any information on the bowls.
 - $Pr(B) = (0.75 + 0.5)0.5 = 0.625$
 - $Pr(B) = 50/80 = 0.625$
- $Pr(B|A)$ = the probability of getting a plain cookie given that Fred has selected bowl 1. $Pr(B|A) = 30/40 = 0.75$

Cookies Answer (II)

Given all this information, we can compute the probability of Fred having selected bowl 1 given that he got a plain cookie, as such:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} = \frac{0.75 \times 0.5}{0.625} = 0.6$$

As we expected, it is more than half.

Exercise: Drug Test

Suppose a certain drug test is 99% accurate, that is, the test will correctly identify a drug user as testing positive 99% of the time, and will correctly identify a non-user as testing negative 99% of the time. Let's assume a corporation decides to test its employees for opium use, and 0.5% of the employees use the drug.

We want to know the probability that, given a positive drug test, an employee is actually a drug user.

Expectation

Let $D = (U, P)$ be a probability distribution. If X is a real random variable, then its **expected value** is:

$$E[X] := \sum_{u \in U} X(u)P[u]$$

Properties

If \mathcal{X} is the image of X , we have:

$$E[X] = \sum_{x \in \mathcal{X}} \sum_{u \in X^{-1}(x)} xP[u] = \sum_{x \in \mathcal{X}} xP[X = x]$$

More generally,

$$E[f(X)] = \sum_{x \in \mathcal{X}} f(x)P[X = x]$$

Examples

Let X be uniformly distributed over $\{1, \dots, n\}$.

$$E[X] = \sum_{x=1}^n x \cdot \frac{1}{n} = \frac{n(n+1)}{2} \cdot \frac{1}{n} = \frac{n+1}{2}$$

Let X denote the value of a die toss. Let A be the event that X is even. X is uniformly distributed over $\{2, 4, 6\}$, and hence

$$E[X|A] = \frac{2+4+6}{3} = 4$$

Similarly, in the conditional probability space given \bar{A} , we see that X is uniformly distributed over $\{1, 3, 5\}$, and hence

$$E[X|\bar{A}] = \frac{1+3+5}{3} = 3$$

Hence

$$E[X] = E[X|A]P[A] + E[X|\bar{A}]P[\bar{A}] = 4 \cdot \frac{1}{2} + 3 \cdot \frac{1}{2} = \frac{7}{2}$$

Properties

First, if X is equal to a constant c (i.e., $X(u) = c$ for all $u \in U$), then $E[X] = E[c] = c$.

Second, if X takes only non-negative values (i.e., $X(u) \geq 0$ all $u \in U$), then $E[X] \geq 0$. Similarly, if X takes only positive values, then $E[X] > 0$.

Linearity of expectation

For real random variables X and Y , and real number a , we have

$$E[X + Y] = E[X] + E[Y] \text{ and } E[aX] = aE[X]$$

If X and Y are independent real random variables, then

$$E[XY] = E[X]E[Y]$$

Exercise: Proofs

Variance

The **variance** of a real random variable X is

$$\text{Var}[X] := E[(X - E[X])^2]$$

It is a measure of the spread or dispersion of the distribution of X around its expected value $E[X]$. Variance is always non-negative.

Properties

Let X be a real random variable, and let a and b be real numbers. Then we have:

- $\text{Var}[X] = E[X^2] - (E[X])^2$
- $\text{Var}[aX] = a^2 \text{Var}[X]$
- $\text{Var}[X + b] = \text{Var}[X]$

Exercise: Proofs

Examples

Let X be uniformly distributed over $\{1, \dots, n\}$.

$$E[X] = \sum_{x=1}^n x \cdot \frac{1}{n} = \frac{n(n+1)}{2} \cdot \frac{1}{n} = \frac{n+1}{2}$$

We also have

$$E[X^2] = \sum_{x=1}^n x^2 \cdot \frac{1}{n} = \frac{n(n+1)(2n+1)}{6} \cdot \frac{1}{n} = \frac{(n+1)(2n+1)}{6}$$

Therefore,

$$\text{Var}[X] = E[X^2] - (E[X])^2 = \frac{n^2 - 1}{12}$$

Theorem: Markov's inequality

Let X be a random variable that takes only non-negative real values. Then for any $t > 0$, we have

$$P[X \geq t] \leq \frac{E[X]}{t}$$

Exercise: Proof

Theorem Chebyshev's inequality

Let X be a real random variable. Then for any $t > 0$, we have:

$$P[|X - E[X]| \geq t] \leq \frac{\text{Var}[X]}{t^2}$$

Exercise: Proof

Theorem: Chernoff bound

Let X_1, \dots, X_n be mutually independent random variables, such that each X_i is 1 with probability p and 0 with probability $q := 1 - p$. Assume that $0 < p < 1$. Also, let \bar{X} be the sample mean of X_1, \dots, X_n . Then for any $\epsilon > 0$, we have:

$$P[\bar{X} - p \geq \epsilon] \leq e^{-n\epsilon^2/2q}$$

$$P[\bar{X} - p \leq -\epsilon] \leq e^{-n\epsilon^2/2p}$$

$$P[|\bar{X} - p| \geq \epsilon] \leq 2 \cdot e^{-n\epsilon^2/2}$$

Exercise: Proof

Birthday Paradox: My bet

When are you born ?



Birthday Paradox & Probabilities (I)

- How many people must be in a room such that the probability p that one has your birthday is $p > .5$?

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Birthday Paradox & Probabilities (I)

- How many people must be in a room such that the probability p that one has your birthday is $p > .5$?
- In a room of n people the probability is $1 - \left(\frac{365-1}{365}\right)^n$.
- So we have:

$$n \geq \frac{\ln\left(\frac{1}{2}\right)}{\ln\left(\frac{365-1}{365}\right)} \approx 252,651 \approx 253$$

Birthday Paradox & Probabilities (II)

- How many people must be in a room such that the probability p that any two share the same birthday is $p > .5$?

Birthday Paradox & Probabilities (II)

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- As stated above, the probability that no two birthdays coincide is

$$1 - p(n) = \bar{p}(n) = \prod_{k=1}^{n-1} \left(1 - \frac{k}{365}\right)$$

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- using the inequality $1 + x < e^x$

$$\bar{p}(n) = \prod_{k=1}^{n-1} \left(1 - \frac{k}{365}\right) < \prod_{k=1}^{n-1} \left(e^{-k/365}\right) = e^{-(n(n-1))/(2 \cdot 365)}$$

$$e^{-(n(n-1))/(2 \cdot 365)} < \frac{1}{2}, \text{ we get } n^2 - n > 2 \cdot 365 \ln 2$$

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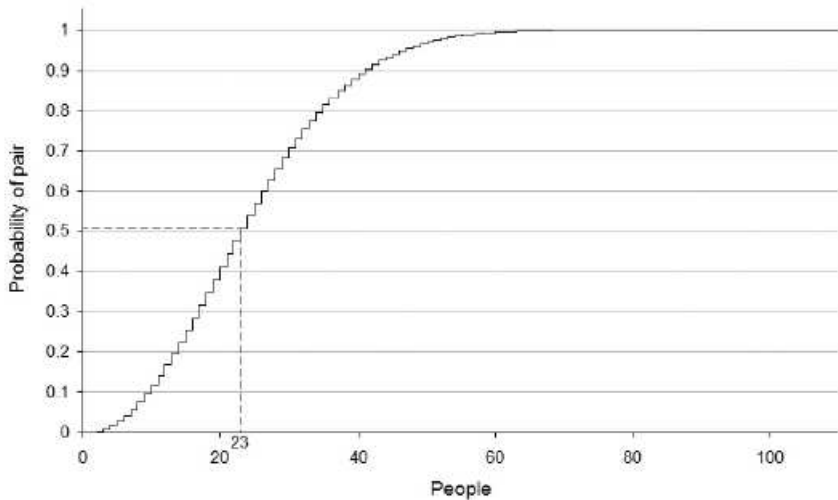
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$$e^{-(n(n-1))/(2 \cdot 365)} < \frac{1}{2}, \text{ we get } n^2 - n > 2 \cdot 365 \ln 2$$

- Hence $n \geq 23$ persons!

$A_n = \{\text{At least two of the } n \text{ people share a birthday}\}$

n	A_n	n	A_n
1	0.00000000	16	0.28360400
2	0.00273972	17	0.31500766
3	0.00820416	18	0.34691141
4	0.01635591	19	0.37911852
5	0.02713557	20	0.41143838
6	0.04046248	21	0.44368833
7	0.05623570	22	0.47569530
8	0.07433529	23	0.50729723
9	0.09462383	24	0.53834425
10	0.11694817	25	0.56869970
11	0.14114137	26	0.59824082
12	0.16702478	27	0.62685928
13	0.19441027	28	0.65446147
14	0.22310251	29	0.68096853
15	0.25290131	30	0.70631624



Birthday Paradox Generalization (I)

Exercise: The setting is that we have q balls. View them as numbered, $1, \dots, q$. We also have N bins, where $N \geq q$. We throw the balls at random into the bins, one by one, beginning with ball 1. At random means that each ball is equally likely to land in any of the N bins, and the probabilities for all the balls are independent. A collision is said to occur if some bin ends up containing at least two balls. We are interested in $C(N, q)$, the probability of a collision. The birthday paradox is the case where $N = 365$. We are asking what is the chance that, in a group of q people, there are two people with the same birthday, assuming birthdays are randomly and independently distributed over the days of the year.

Birthday Paradox Generalization (II)

Let $C(N, q)$ denote the probability of at least one collision when we throw $q \geq 1$ balls at random into $N \geq q$ buckets. Then

$$C(N, q) \leq \frac{q(q-1)}{2N}$$

$$C(N, q) \geq 1 - e^{q(q-1)/2N}$$

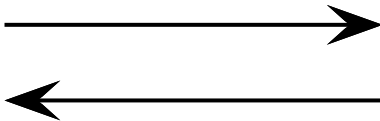
Also if $1 \leq q \leq \sqrt{2N}$ then $C(N, q) \geq 0.3 \cdot \frac{q(q-1)}{N}$

Hint: first prove the inequality $(1 - 1/e) \cdot x \leq 1 - e^{-x} \leq x$

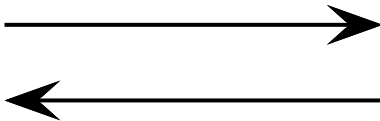
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Description of Problem



Description of Problem



Intruder



Description of Problem



Intruder



Description of Problem



Intruder



Message cannot be understood by anyone else

Notations

If m is the message to be encrypted (also known as the “**plain-text**” or the “**clear-text**” then $c = E_{k_e}(m, r)$ is the encrypted message or “**cipher-text**” with the key k_e . The decryption function is denoted by $D_{k_d}(c)$

$k_e = k_d$ symmetric encryption

$k_e \neq k_d$ asymmetric encryption

A unique m satisfies the relation (with possibly several r)

→ At least an exhaustive search on m and r can lead to m !

⇒ unconditional secrecy is impossible, we need algorithmic assumptions

Perfect Security (Shannon)

Definition

Let $m \in M$ be a random message and $c \in C$ be the cipher-text of m , that is, $c = E_k(m)$. For any $m' \in M$ and $c' \in C$, an encryption system is called **perfectly secure** if from the perspective of the attacker,

$$\Pr(m = m' | c = c') = \Pr(m = m')$$

This means that Eve's probability of guessing m remains unchanged after seeing any particular outcome $c = c'$.

Exercise: Message are composed of $\{0, 1\}$, keys are $\{A, B\}$ and we know $P(0) = 1/4$, $P(1) = 3/4$, $P(A) = 1/4$, $P(B) = 3/4$. The encryption is defined by:

$$E_A(0) = a, E_A(1) = b, E_B(0) = b, E_B(1) = a$$

Is this encryption perfectly secure?

One Time Pad (OTP)

The One Time Pad encryption function is easily described; simply take the exclusive OR of the message string m and the key k .

(Vernam encryption)

- $E_k(m) = m \oplus k$
- $D_k(c) = c \oplus k$

Exercise: Prove that OTP is perfectly secure WITH JEAN-LOUIS on Monday.

Negligible Functions

We call a function $\mu : \mathbb{N} \rightarrow \mathbb{R}^+$ negligible if for every positive polynomial p there exists an N such that for all $n > N$

$$\mu(n) < \frac{1}{p(n)}$$

Exercise: Prove or disprove:

- The function $f(n) := \left(\frac{1}{2}\right)^n$ is negligible.
- The function $f(n) := 2^{-\sqrt{n}}$ is negligible.
- The function $f(n) := n^{-\log n}$ is negligible.

Noticeable Functions

Instead of "there exists an N such that for all $n > N$ " we will in the following often say "for all sufficiently large n ".

We call a function $\nu : \mathbb{N} \rightarrow \mathbb{R}$ noticeable if there exists a positive polynomial p such that for all sufficiently large n , we have:

$$\nu(n) > \frac{1}{p(n)}$$

Note: A function can be neither noticeable nor negligible.

Exercises

Prove or disprove the following statements:

- 1 If both $f, g \geq 0$ are noticeable, then $f - g$ and $f + g$ are noticeable.
- 2 If both $f, g \geq 0$ are not noticeable, then $f - g$ is not noticeable.
- 3 If both $f, g \geq 0$ are not noticeable, then $f + g$ is not noticeable.
- 4 If $f \geq 0$ is noticeable, and $g \geq 0$ is negligible, then $f.g$ is negligible.
- 5 If both $f, g > 0$ are negligible, then f/g is noticeable.

Thank you for your attention.

Questions ?