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Breaking Ciphers with COPACOBANA
A Cost-Optimized Parallel Code Breaker

or

How to Break DES for 8,980 €

CHES 2006, Yokohama, October 10-13, 2006

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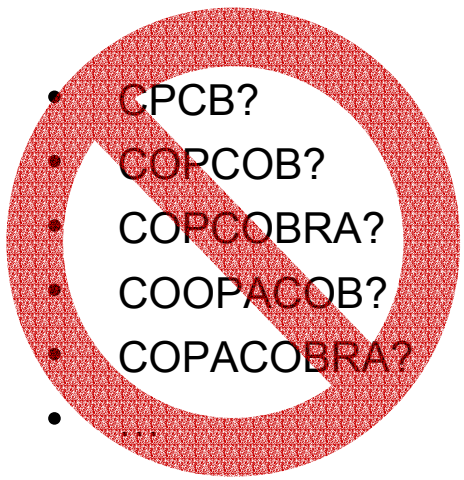
Acknowledgements

- Joint project with the University of Kiel (Gerd Pfeiffer, Manfred Schimmler)
- Special thanks to François-Xavier Standaert and Jean-Jacques Quisquater (Universitè Catholique de Louvain) for the core of the DES architecture

Introduction: A Naming Tale

What does COPACOBANA stand for?

Possible abbr. of „Cost-optimized Parallel Code-Breaker“:



- CPCB?
- COPCOB?
- COPCOBRA?
- COOPACOB?
- COPACOBRA?
- …

► COPACOBANA

What‘s in a name?

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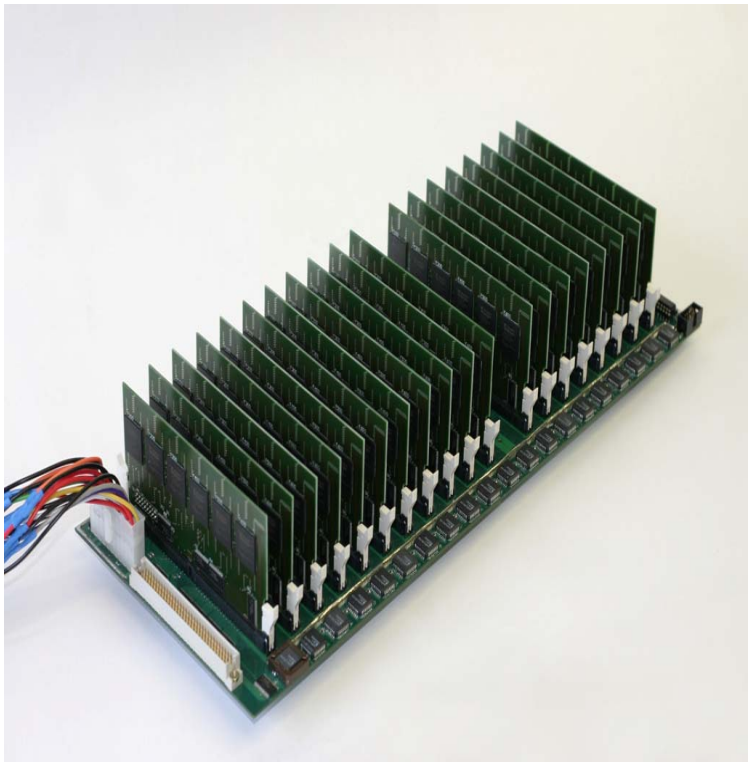

Copacobana

Outline

- Security vs. Cost
- COPACOBANA Design
- Application 1: Brute Force Attack on DES
- Application 2: ECC Attack
- Conclusion and Outlook

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When is a Cipher Secure?

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Symmetric ciphers

- (hopefully) only brute-force attack possible
- „secure“ key lengths: 112…256 bit (attack compl. 2^{112}…2^{256})
- but in practice wide variety of keys: AES, DES, RC4, A5, MD5, SHA-1, … (attack compl. 2^{56}…2^{256})

Asymmetric ciphers (RSA, ECC, DL)

- algorithmic attacks (e.g., factorization) dictate larger keys
- key lengths in practice:
  - RSA, DL: 1024 … 4096 bit
  - ECC: 160 … 256 bit
- attack complexities: 2^{80} (?) … 2^{128}

Security and Computation

- Traditional: security of ciphers = **complexity** of attacks
- However: What really matters are the **costs** of an attack
- State-of-the-art
  - < 2^{50} steps can be done with PC networks (more or less conveniently)
  - > 2^{80} steps are very hard with today‘s technology (probably also for intelligence agencies)

Major question: Cost of attack for ciphers with 50…80 bit security (RSA1024, ECC160, SHA-1, DES, A5, …)

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Introduction: Massive Computing

Supercomputers (Cray, SG, …)

- General (= complex & expensive) parallel computing architectures
- fast I/O, large memory, easy to program

► poor cost-performance ratio for (most) cryptanalysis

Distributed computing (conventional PCs)

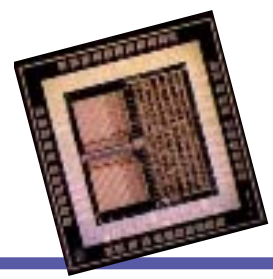
- Dedicated clients in clusters, or
- Using PC's idle time: E.g., SETI@home (BOINC framework)

► Problem of motivation, confidentiality issues

Special-purpose hardware

- ASIC - Application Specific Integrated Circuits (high NRE)
- FPGA - Field Programmable Gate Arrays (low NRE)

► best cost-performance ratio



Cryptanalysis of Modern Ciphers: Basics

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Security of ciphers is related to complexity of attacks:

- **Symmetric ciphers:**
  - „Good“ ciphers: only exhaustive key search possible
  - an exhaustive key search should be infeasible
  - Secure key lengths: 80…256 bit
  - But many legacy systems with 56…64 bit (DES and such)

- **Asymmetric ciphers (e.g., RSA, ECC)**
  - longer keys due to analytical attacks
  - Secure key lengths
    - RSA: 1024…4096
    - ECC: 130-256 bit

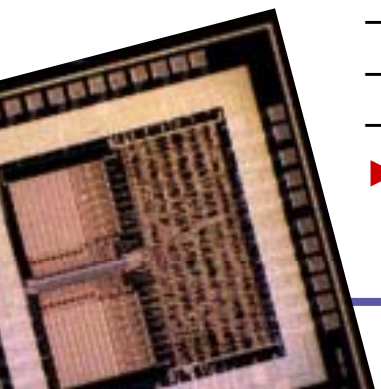
Cryptanalysis of Modern Ciphers: Hardware

Possible solutions to computational extensive problems:

- Large supercomputers:
  - Complex and expensive parallel computing architectures
  - Fast I/O, large memory, easy to program
  - E.g., Cray-XD1
  - ► Too complex for (most) cryptanalysis (bad cost-performance ratio)

- Distributed computing (conventional PCs):
  - Dedicated clients in clusters, or
  - Using PC's idle time: E.g., SETI@home (BOINC framework)
  - ► Problem of motivating for cryptanalytic challenges, confidentiality issues

- Special purpose hardware:
  - Application Specific Integrated Circuits (ASICs, high NRE)
  - Field Programmable Gate Arrays (FPGAs, low NRE)
  - Optimized for one particular objective
  - ► Tradeoff between reprogrammability and price per piece, best cost-performance ratio



Introduction: Advantage of Hardware

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Cost-performance ratio of DES[1)]: PC vs. FPGA

- DES encryptions / decryptions per second

Pentium4@3GHz: $\approx 2 \times 10^6$
price per device (retail): € 80

Xilinx XC3S1000@100MHz $\approx 400 \times 10^6$
price per device (retail): € 40

► Cost-performance ratio differs by 2-3 orders of magnitude!

1) Based on actual optimized implementations

COPACOBANA: Design Principles

- Ability to perform $\geq 2^{56}$ crypto operations
- Re-programmable: Applicable to many ciphers
- Strictly optimized cost-performance ratio:
  - off-the-shelf hardware (low-cost)
  - many logic resources (performance)
- < 9,000 € (including fabrication and material cost)
- Parallel architecture, based on 120 low-cost FPGAs
- Sacrifices
  - no global memory
  - no high-speed communication („only“ Mbit/s)

COPACOBANA: Realization

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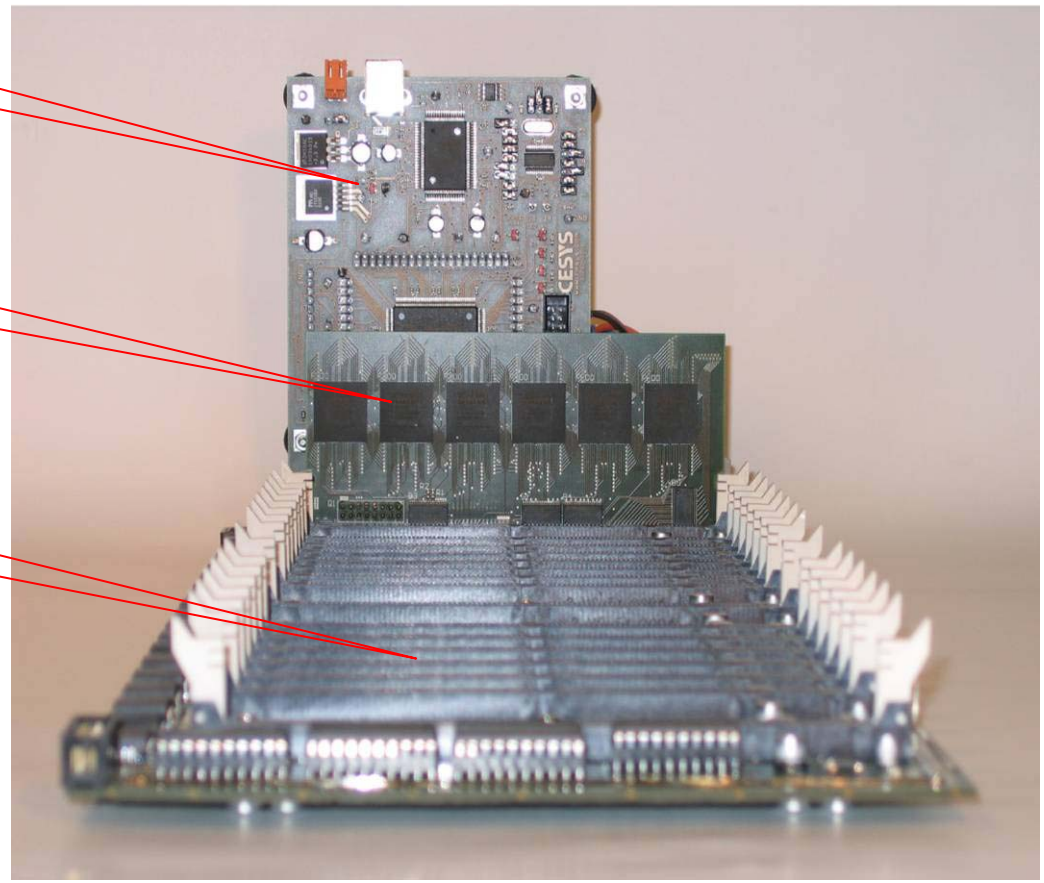
Controller board

FPGA module

Backplane

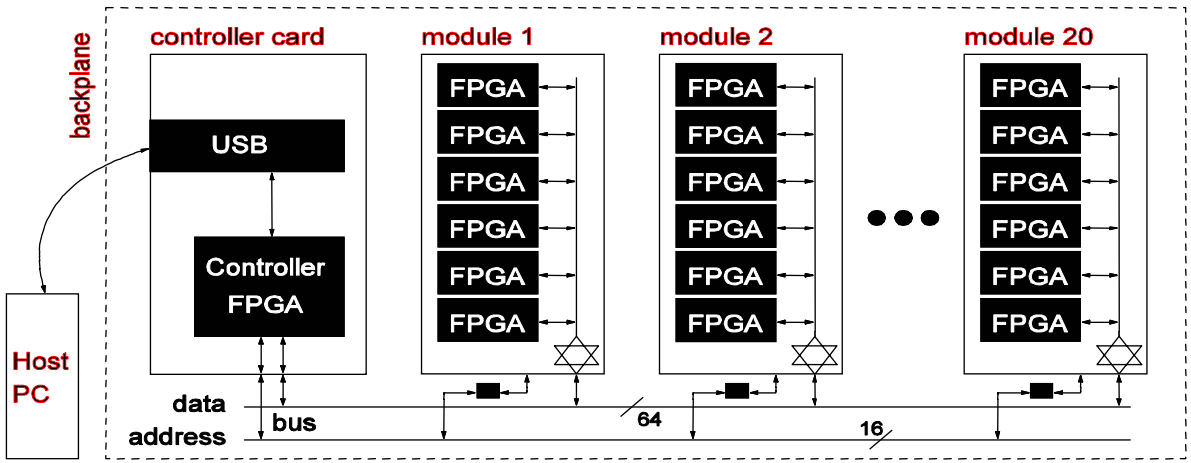


Scales easily:

- 20 FPGA modules/machine (120 FPGAs/machine)
- multiple machines via USB

COPACOBANA: Basic Design

- Modular design:
  1. Backplane
  2. FPGA modules (each with 6 low-cost FPGAs)
  3. Controller card with USB interface



- Easily extendable:
  - Up to 20 FPGA modules with 6 FPGAs each
  - Connect multiple COPACOBANAs via USB

COPACOBANA: FPGA Modules

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Functionality:

- 6x Spartan-3 FPGAs (xc3s1000) per module
  - BGA packaging (FT256)
  - Internal clock rate up to 300 MHz
- Addressing:
  - HW decoded adress of FPGA modules (GAL on backplane)
  - HW decoded adress of single FPGA
  - Further addresses (5-bit) for FPGA-internal processing
- 64-bit data connection to backplane (bi-directional)
- 64-bit local bus (per module)
- Host cryptanalytical applications, e.g.,
  - Key search engines for DES
  - ECM engines
  - Pollard Rho engines

COPACOBANA: FPGA Modules (Schematic)

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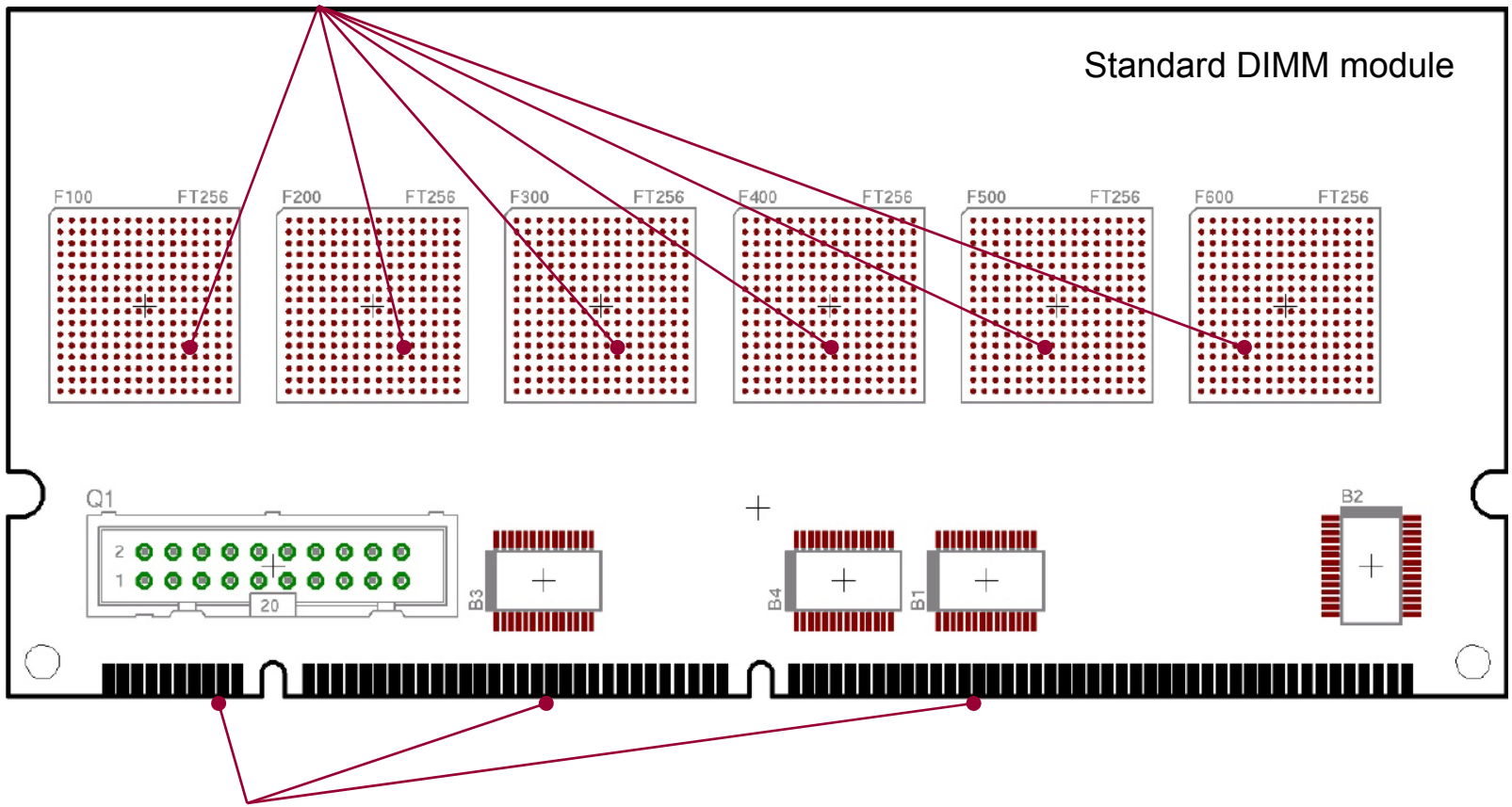
6x Spartan 3 FPGA (xc3s1000, FT256 packaging)



Connection to backplane (64-bit data bus)

COPACOBANA: Alpha Prototype

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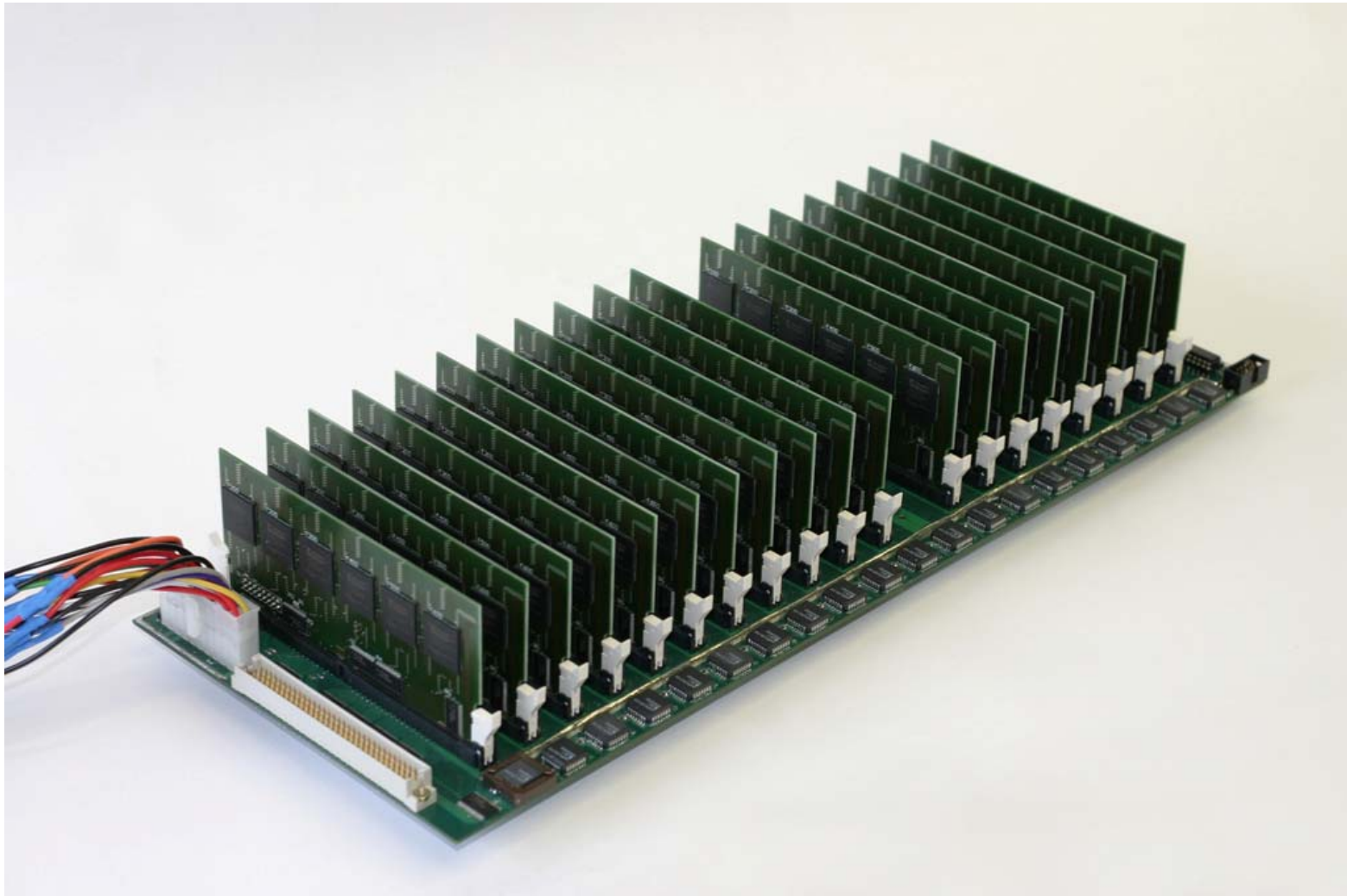

COPACOBANA: Controller Module

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Functionality:

- Programming of FPGAs:
  - Individual (download per FPGA)
  - Concurrent (download to all/ subset FPGAs)
- Communication with FPGAs:
  - Initialization of FPGA logic
  - Polling of FPGAs
- Communication with host-PC:
  - Redirecting results
  - Simple pre- and post processing

COPACOBANA: Applications

First flexible cryptanalytical machine outside government agencies

1. Exhaustive key search of DES
   - ciphers with 2^{56}…2^{64} attack steps possible
2. Real-world systems such as ePass, Norton Diskreet, …
3. Elliptic Curve Discrete Logarithm Problem (ECDLP)
   - Parallelized Pollard's Rho
4. Factorization
   - Parallelized Elliptic Curve Method (ECM) as subroutine for GNFS (see GMU's talk later)

Attacks feasible

Robust security estimations

Improves other attacks

Outline

- Security vs. Cost
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Cryptanalytical Applications: Attacks on DES

Data Encryption Standard (DES):

- Block cipher with 56-bit key
- Expired standard, but still used (legacy products, ePass, Norton Diskreet, …)

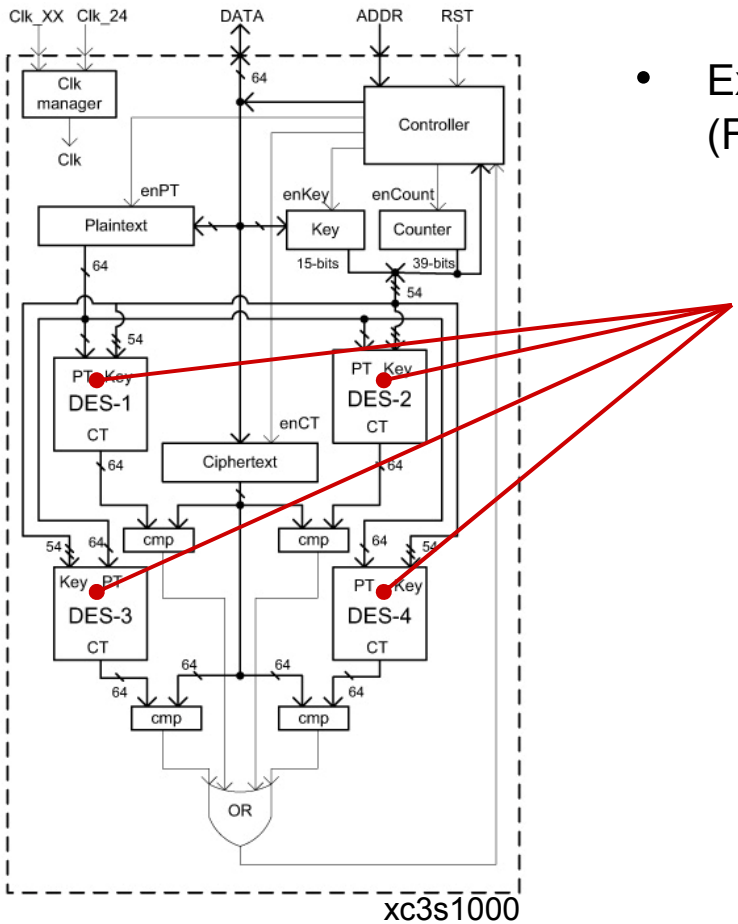
Exhaustive key search (conventional technology):

- Check 2^{55} keys on average
- PC (e.g., Pentium4@3GHz) ≈ 2 mio. keys/sec
- Average key search with one PC ≈ 2^{34} sec = 545 years!

► Can do much better with special-purpose hardware!

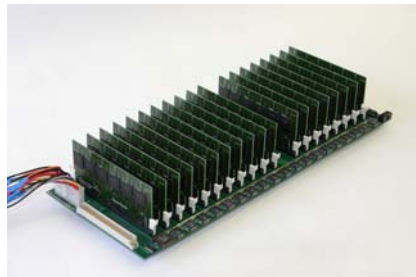
Attacks on DES

FPGA-based attacks on the Data Encryption Standard (DES):



- Exhaustive key search (FPGA based):
  - 4 completely pipelined DES engines per FPGA (courtesy of the crypto group of UCL)
  - one key per clock cycle per DES engine
  - One FPGA@100MHz: 400 mio. keys/ sec

Attacks on DES



- COPACOBANA: average key search of **8.7 days** @ 100 MHz
- Somewhat higher clock rates possible
- FPGA vs. PC (average key search in 8.7 days)
  - 22,865 Pentium 4 (€ 3.6 million incl. overhead)

    or
  - COPACOBANA (total cost € 9000 incl. overhead)
- Alpha version of COPACABANA runs stable
- Life attack at http://www.copacobana.org/live

A Historical Perspective: The Power of Moore's Law

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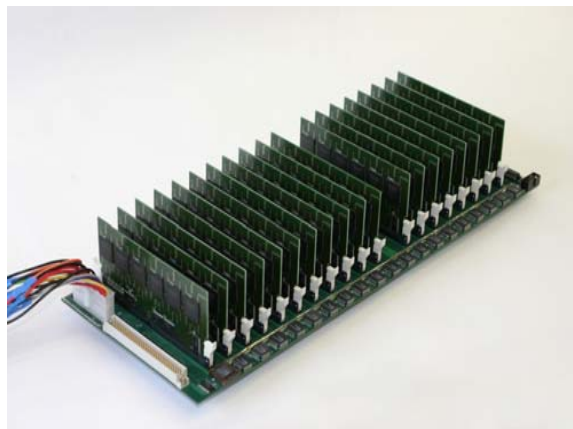
DeepCrack, 1998

$250,000

COPACOBANA, 2006

$10,000



Moore' Law: 50% cost reduction / 1.5 years

2006-1998 = 8 years ≈ **5** x 1.5 years

Prediction: $250,000 / 2^5 ≈ $8,000 (close to actual $10,000)

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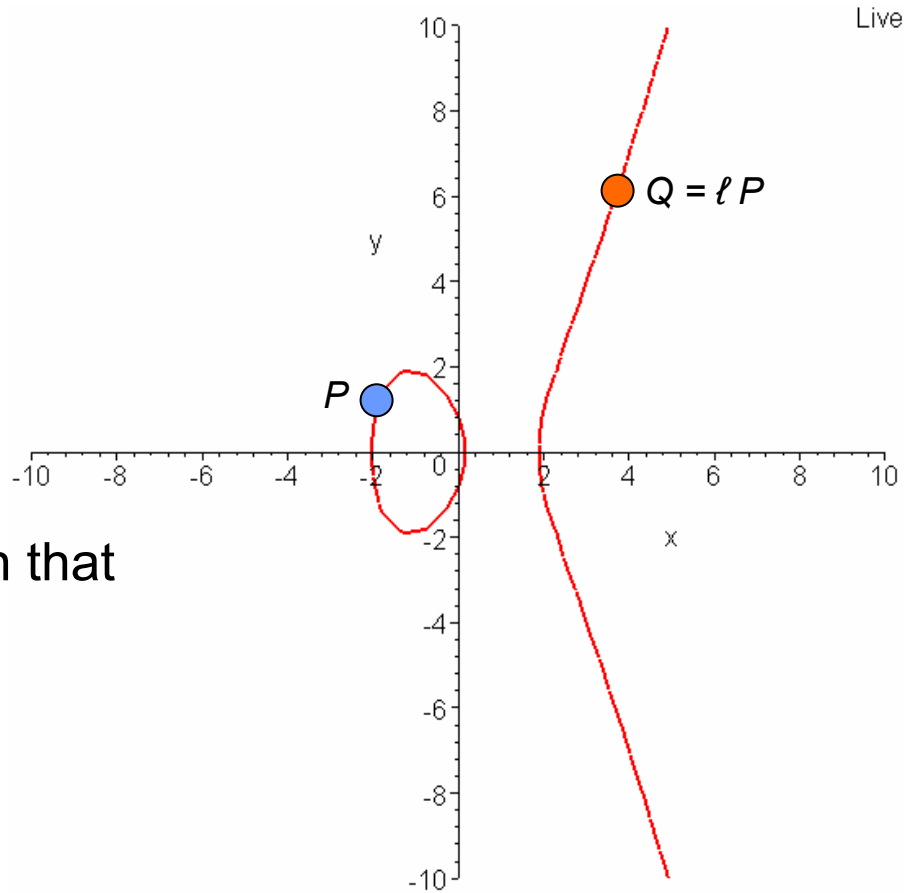
ECDL Problem

- Many real-world applications rely on hardness of ECDLP
  - ECDSA,
  - ECDH,
  - …
- Let P be a generator. Determine *discrete logarithm* ℓ of a point Q such that

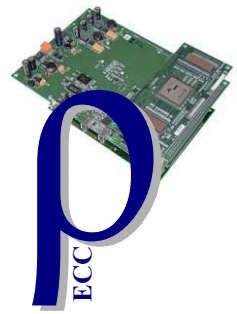
$$Q = \ell P.$$



Generic ECDLP Attacks

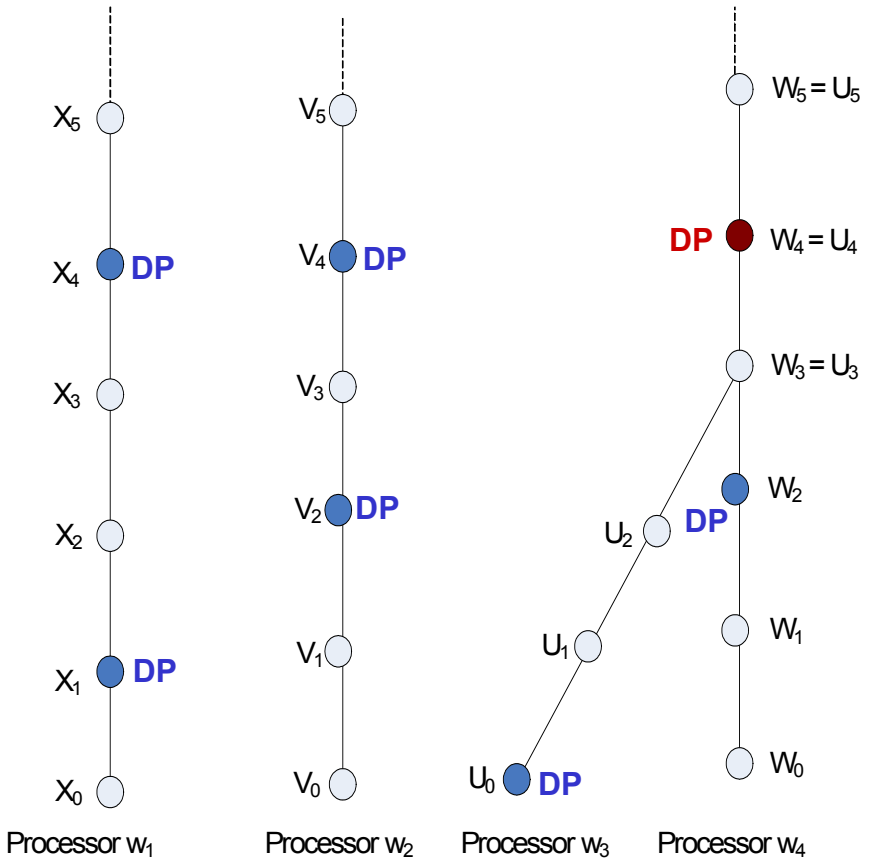
If parameters are chosen with care, only generic attacks are possible

1. **Naïve Search**: Sequentially test P, *2P, 3P, 4P*,…
   - Brute force attack is infeasible if #E $\geq 2^{80}$
2. **Shank's Baby-Step-Giant-Step Method**
   - Complexity in time AND memory of about $\sqrt{}$ #E
3. **Pollard's Rho method** (ρ)
   - Most efficient algorithm for general ECDLP
   - Complexity of $\sqrt{}$ #E



Note: All attacks are *exponentia*l in the bit length of the group order

Multi Processor Pollard Rho (MPPR)

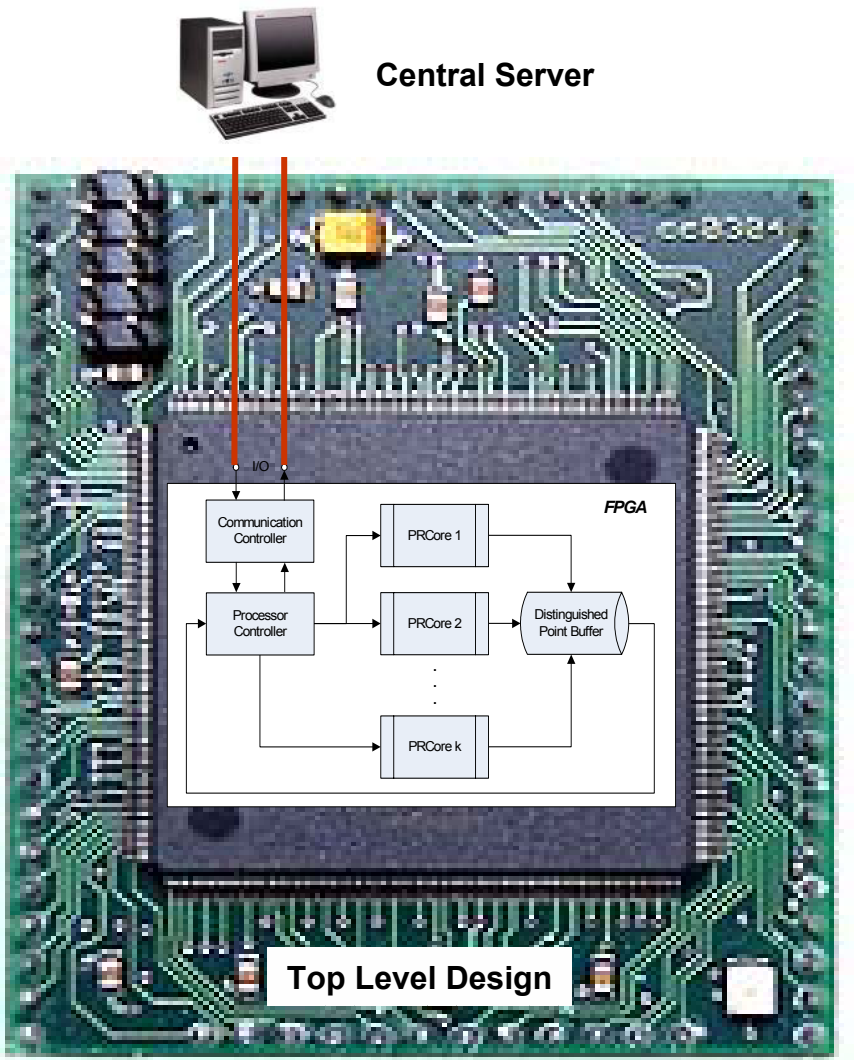


Colliding DP trails of multiple processors w_i

- Best known attack against general ECC
- Proposed by van Oorschot/Wiener in 1999
- Processors have individual search paths for “Distinguished Points” (DP)
- DP are stored at central server
- Duplicate DP = ECDLP solution

Ideal parallelizatin: speed up linear in number of employed processors

Hardware Implementation (Top Layer)



Neither

- fastest, nor
- smallest

implementations is needed, but

- **Time-Area Optimum**.

- Each FPGA: multiple point engines (PRCore) each computing a separate trail.
- All cores store distinguished points in a shared point buffer.
- Buffer locking & host communication are needed to transfer DPs to the server.
- FPGA to Host communication via serial (for debugging) or proprietary bus interface.

ECDLP Attack Comparison: SW vs. HW for $10.000

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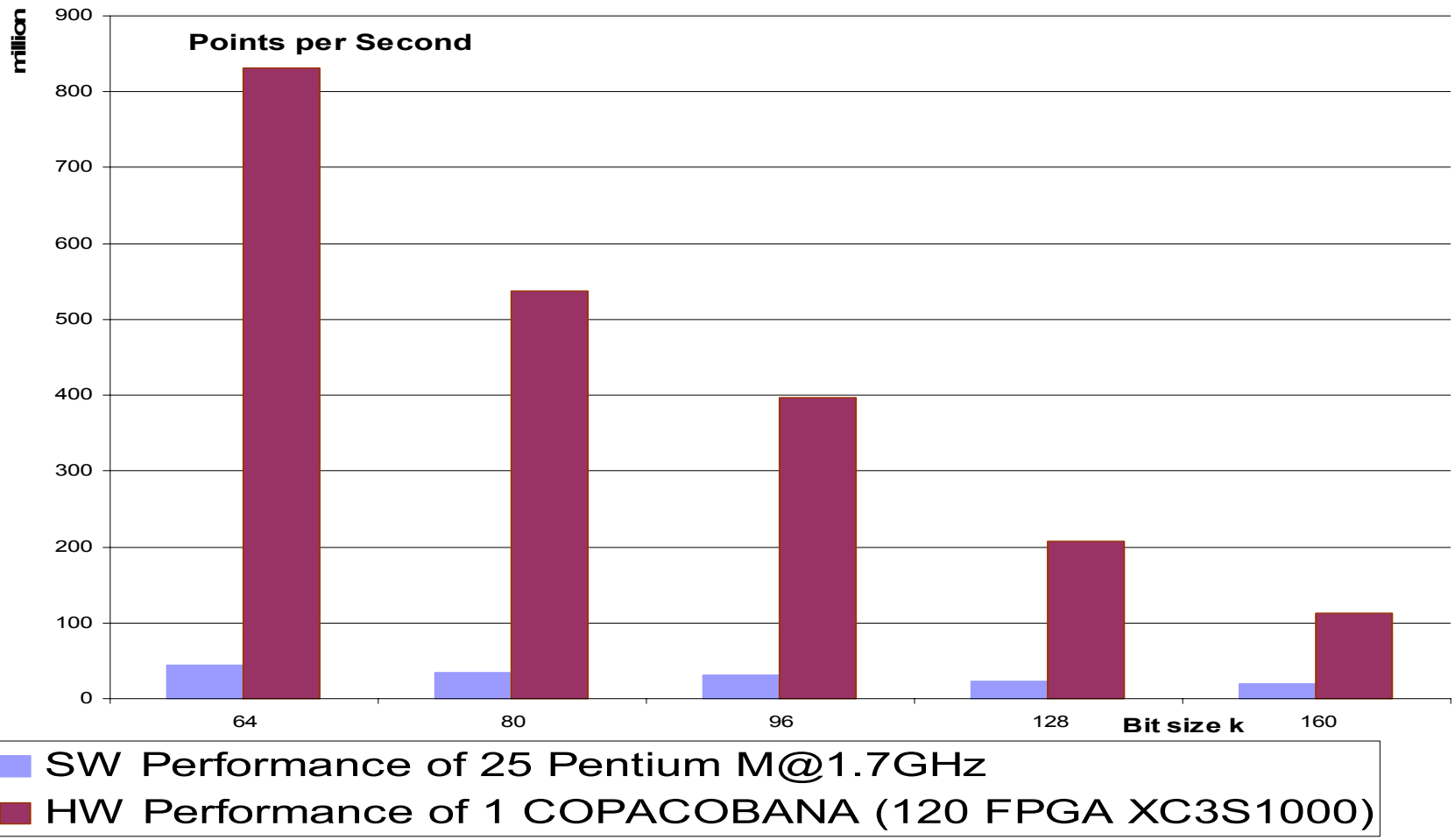

ECDLP Attacks for US$ 1 million

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Bit size k	SW Reference Pentium M@1.7	COPACOBANA	est. ASIC
80	40.6 h	2.58 h	-
96	8.04 d	14.8 h	-
112 (SEC-1)*	6.48 y	262 d	1.29 d
128	1.94 $x10^3$ y	213 y	1.03 y
160	1.51 x 10^8 y	2.58 x 10^7 y	1.24 x 10^5 y

* SECG (STANDARDS FOR EFFICIENT CRYPTOGRAPHY)

Conclusion

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Pros and cons of COPACOBANA:

+ efficient hardware architecture
+ reprogrammable hardware (FPGAs)
+ very cheap to produce
+ extendable (per architecture, multiple architectures, …)
+ design option: local memory
+ design option: upgrade to future FPGA technologies
+ not restriced to code-breaking

- no global memory (only controller/ host-PC)
- relatively slow communication
- suited only for particular problems (e.g., cryptanalysis)
- requires programming in VHDL

Conclusion – COPACOBANA

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- Results
  - DES in 8.6 days
  - ECCp163 attack currently ≈ $ 1 trillion ($$10^{12}$$)
    - Moore‘s Law: ECC 160 will stay secure for ≈ 20 years
  - ECC112 (SEC-1 standard): insecure!
  - possibly real-time attack against ePass
- Many marginally weak ciphers are breakable
- „Strong“ ciphers (AES, RSA-1024, ECC-163, …) not breakable, but robust estimates by extrapolation of COPACOBANA results
- Several future applications are currently investigated
- Pictures, papers, and much more at www.copacobana.org
- We are looking for partners for other applications

Outlook

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Future work includes

- Completion of the COPACOBANA platform:
  - harden communication framework
  - run complete DES key search with 120 FPGAs
  - run (previous) ECC challenges on COPACOBANA, analyze SECG 80, 112, 128
  - implement parallel ECM for COPACOBANA
- Optimization of VHDL implementations
- Optimization of hardware platform (beyond prototype)
- Hardware based attacks demand for re-evaluation of security of, e.g., ECC
- Further applications: Smith-Waterman algorithm for scanning DNA sequences against databases


Questions?
http://www.copacobana.org