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für IT Sicherheit

Breaking Ciphers with COPACOBANA
A Cost-Optimized Parallel Code Breaker

or

How to Break DES for 8,980 €

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Acknowledgements

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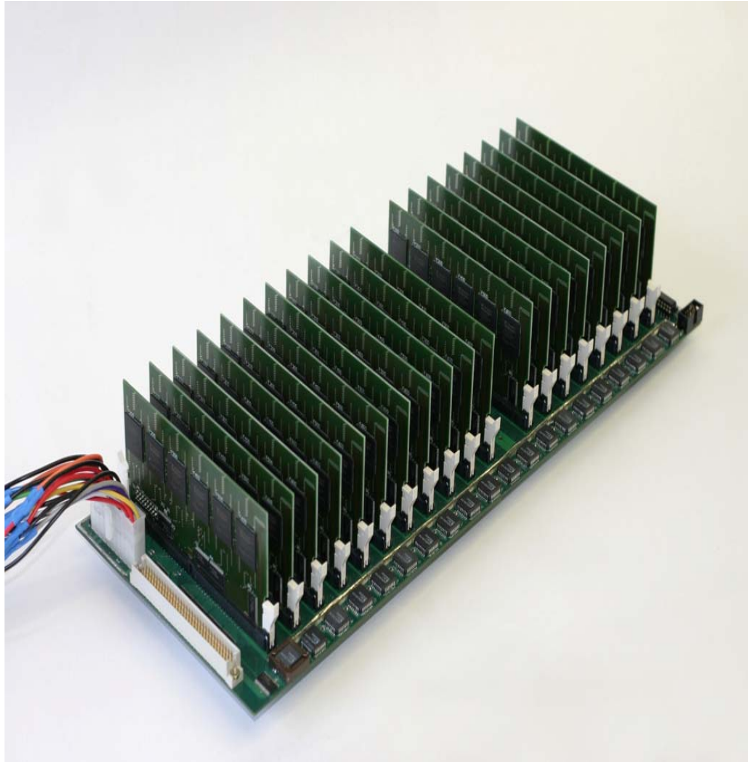
- Special thanks to François-Xavier Standaert and Jean-Jacques Quisquater (Universitè Catholique de Louvain) for the core of the DES architecture

What's in a name?



Copacobana

Outline

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

When is a Cipher Secure?

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Symmetric ciphers

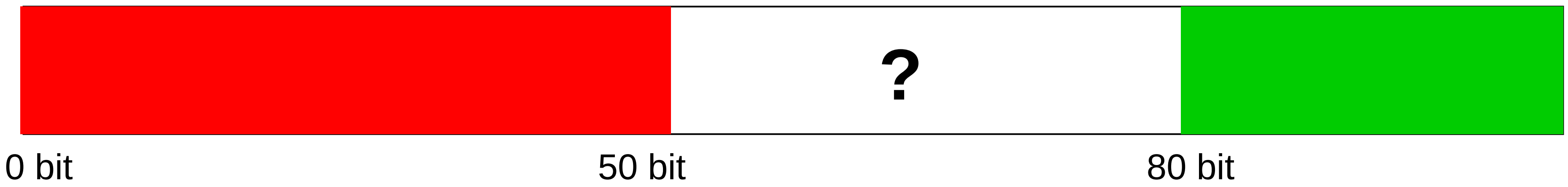
- (hopefully) only brute-force attack possible
- „secure“ key lengths: 112…256 bit (attack compl. 2^{112}…2^{256})
- but in practice wide variety of keys: AES, DES, RC4, A5, MD5, SHA-1, … (attack compl. 2^{56}…2^{256})

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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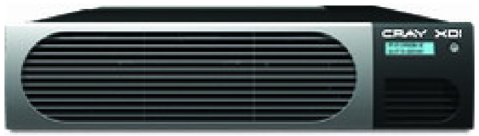
Introduction: Massive Computing

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

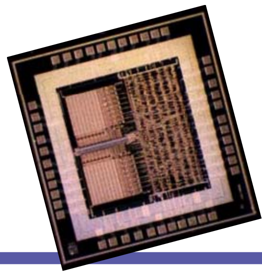
– Using PC's idle time: E.g., SETI@home (BOINC framework)

► 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

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Introduction: Advantage of Hardware

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

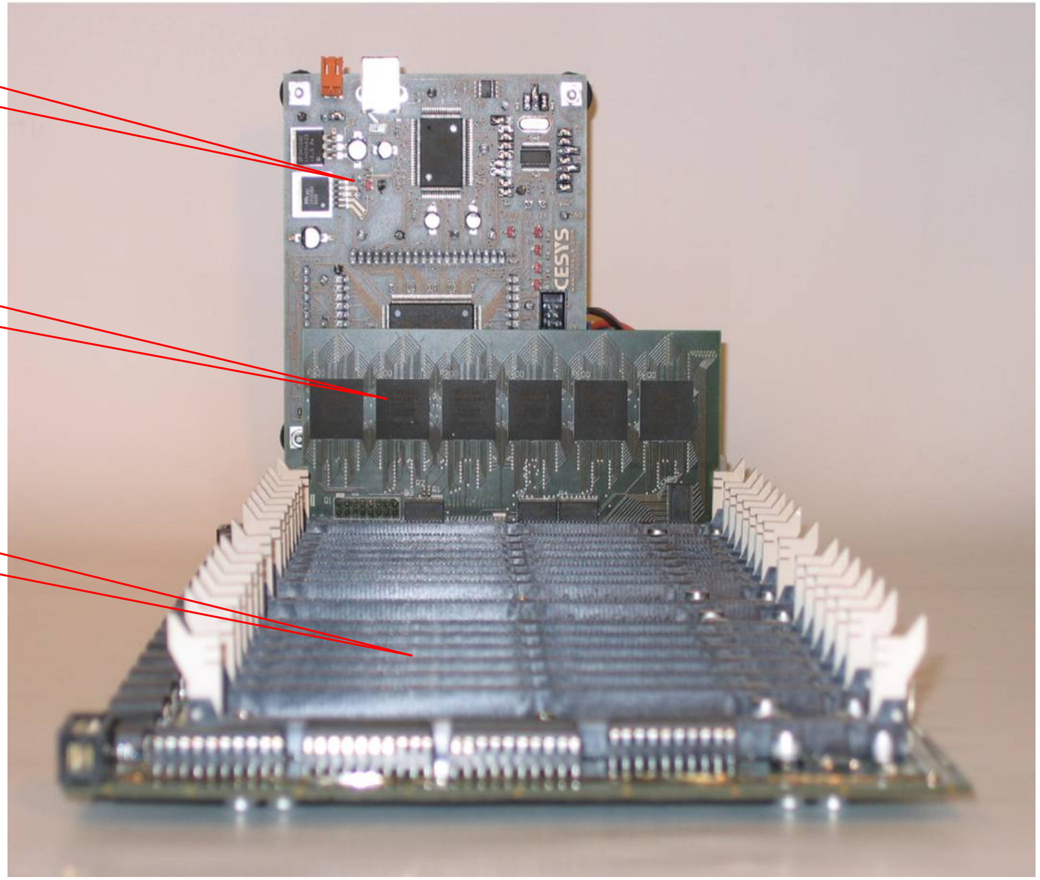
- Ability to perform $\geq 2^{56}$ crypto operations
- Re-programmable: Applicable to many ciphers
- Strictly optimized cost-performance ratio:
  - off-the-shelf hardware (low-cost)
  - many logic resources (performance)
- < 9,000 € (including fabrication and material cost)
- Parallel architecture, based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

COPACOBANA: Realization

Controller board

FPGA module

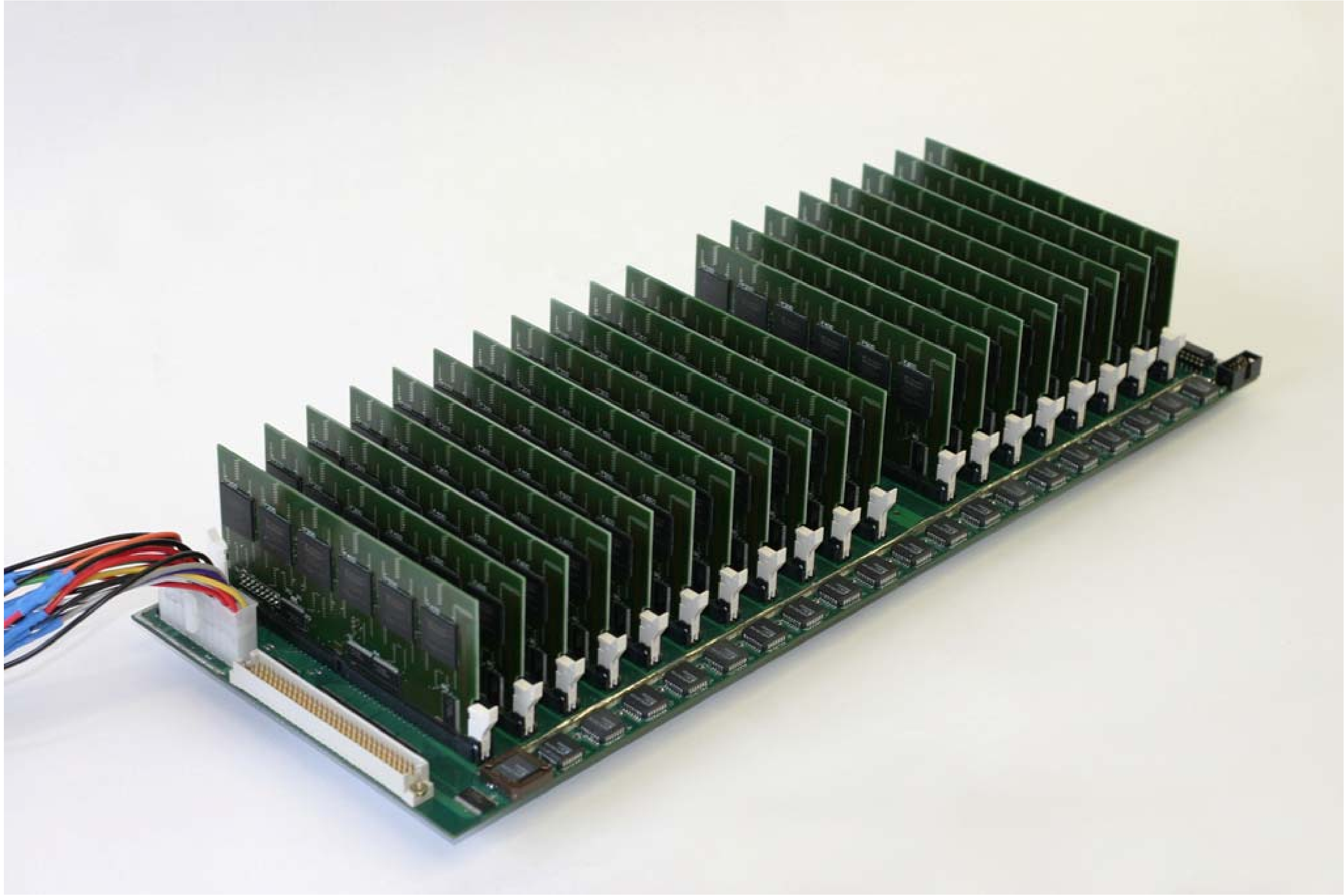
Backplane



Scales easily:

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

COPACOBANA: Alpha Prototype



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

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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, …)

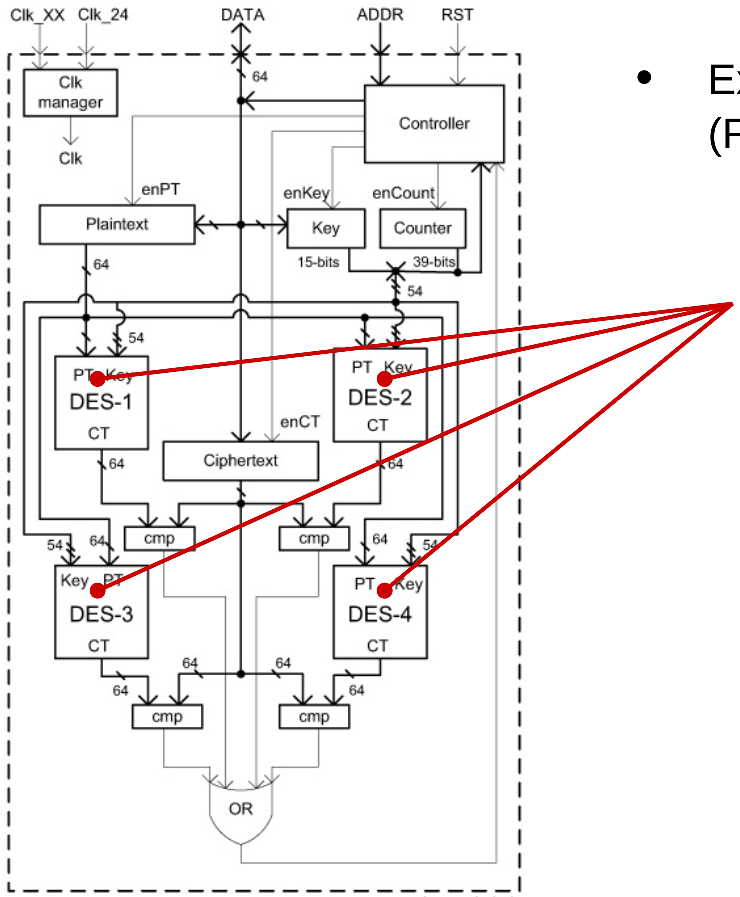
Exhaustive key search (conventional technology):

- 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

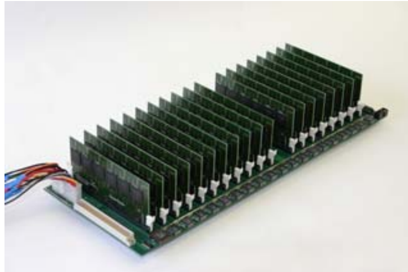
FPGA-based attacks on the Data Encryption Standard (DES):



- 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

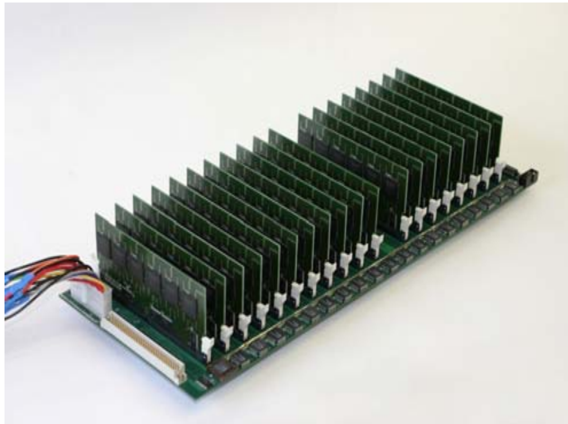
A Historical Perspective: The Power of Moore‘s Law

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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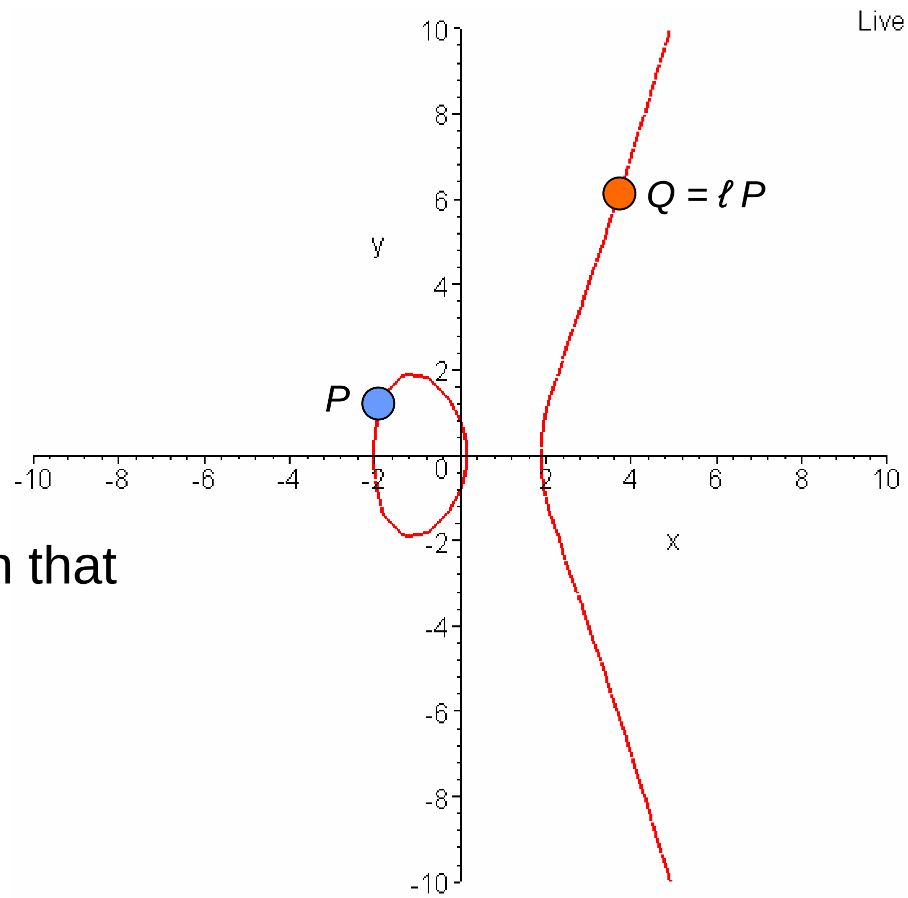
ECDL Problem

- 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

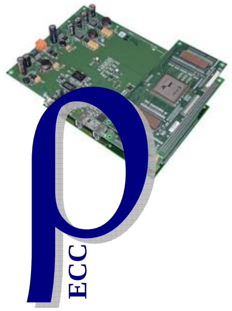
$$Q = \ell P.$$



Generic ECDLP Attacks

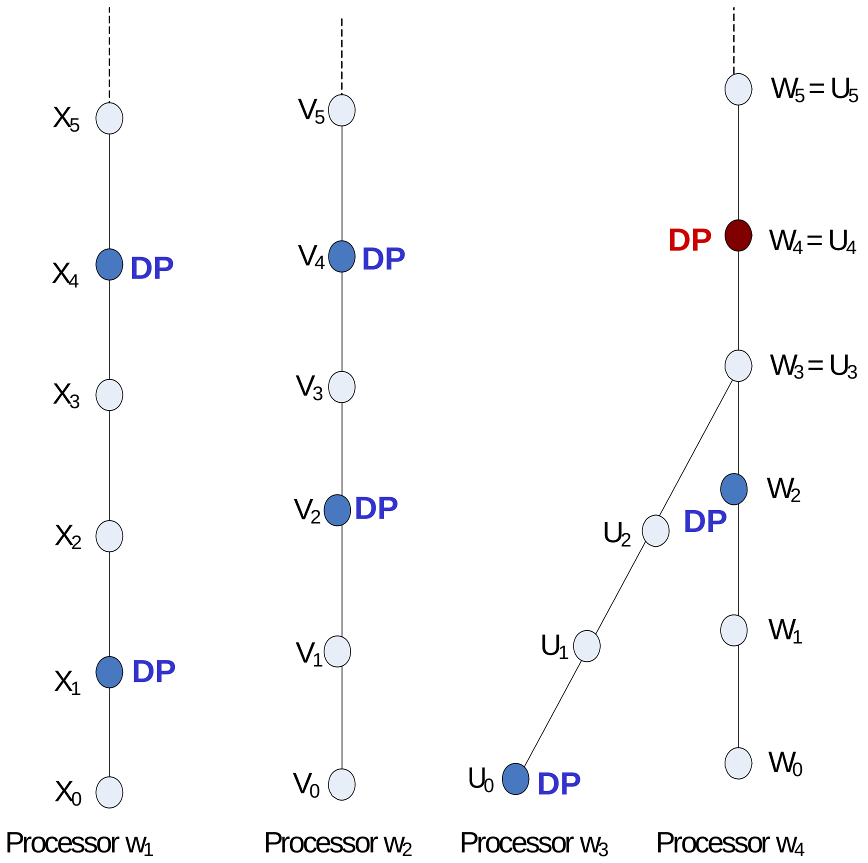
If parameters are chosen with care, only generic attacks are possible

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



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

Multi Processor Pollard Rho (MPPR)

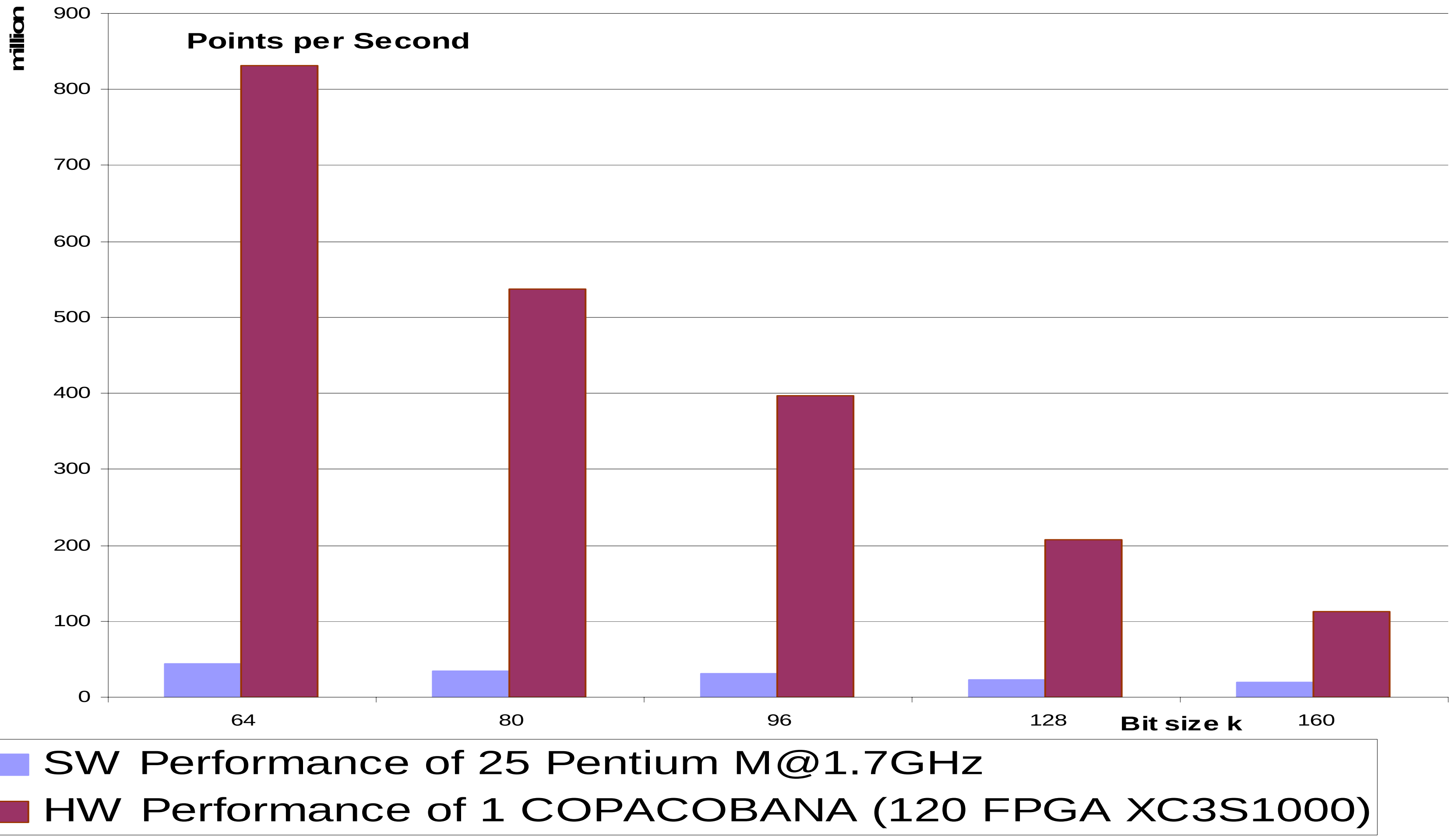


Colliding DP trails of multiple processors w_i

- 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

ECDLP Attack Comparison: SW vs. HW for $10.000



ECDLP Attacks for US$ 1 million

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	1.94×10^3 y	213 y	1.03 y
160	1.51×10^8 y	2.58×10^7 y	1.24×10^5 y

* SECG (STANDARDS FOR EFFICIENT CRYPTOGRAPHY)

Conclusion – COPACOBANA

- 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