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European Competence Center for IT Security

Light-Weight Cryptography for Ubiquitous Computing

Securing Cyberspace Workshop IV: Special purpose hardware for cryptography – Attacks and Applications
University of California at Los Angeles, December 4, 2006

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Joint work with

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- Gregor Leander
- Axel Poschmann
- Kai Schramm

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1. Security in Embedded Systems
2. Light-Weight Block Ciphers
3. Light-Weight Asymmetric Cryptography

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1. **Security in Embedded Systems**
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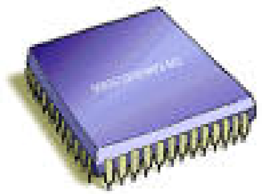
What are EmbeddedSystems?

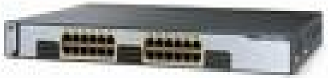
 +  = Embedded System

- „Processor hidden in a product“, or
- „A computer that doesn‘t look like a computer“

Characteristics of Embedded Systems

- Single purpose device





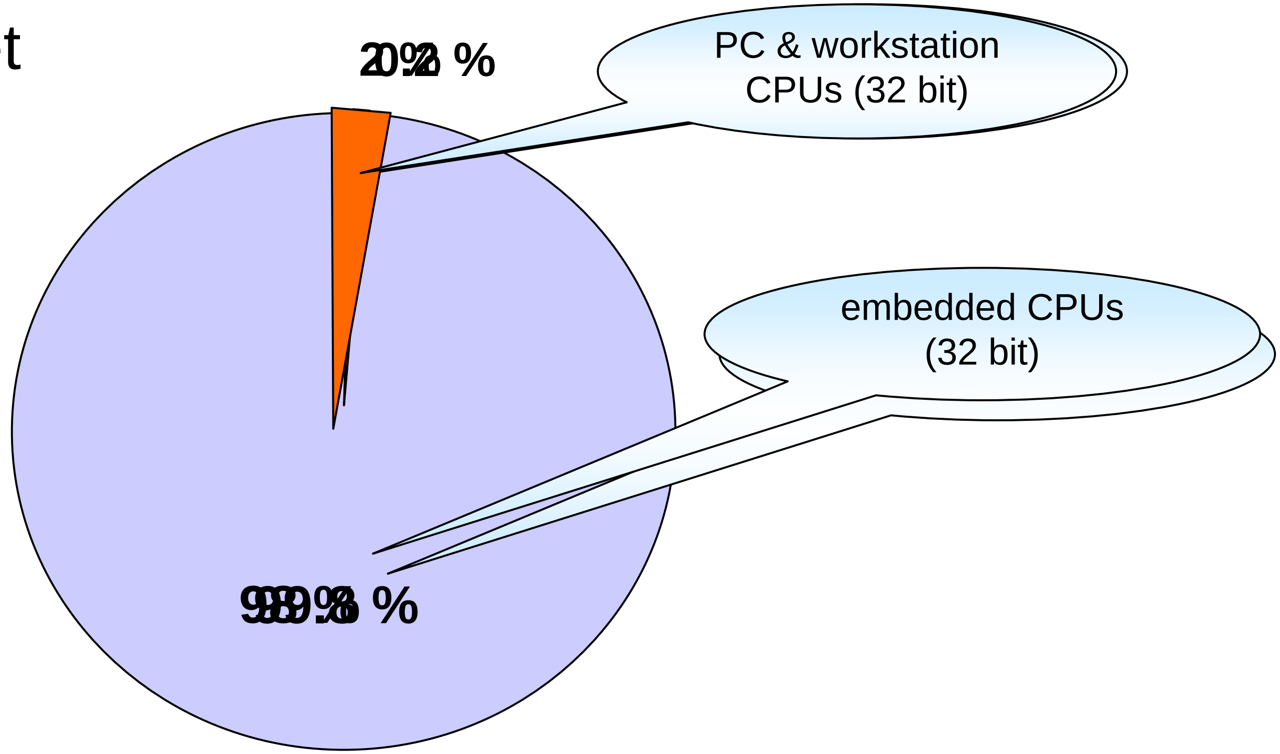

- Interacts with the world

- many,many applications

Is this really important ?

current CPU market

by the numbers



So, how does embedded technology affect the future IT landscape?

Brave New Pervasive World

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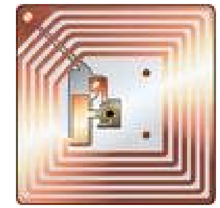
Light-Weight Cryptography

- "We need security with less than 2000 gates"
  Sanjay Sarma, AUTO-ID Labs, CHES 2002



- $3 trillions annually due to product piracy* (> US budget '07)

*Source: www.bascap.com

⇒ Authentication & identification problem: can both be fixed with cryptography

⇒ How cheap can we make crypto algorithms?

Strong Identification (w/ symmetric crypto)

r ←

$e_k(r) = y$ →

1. random challenge r
2. encrypted response y
3. verification

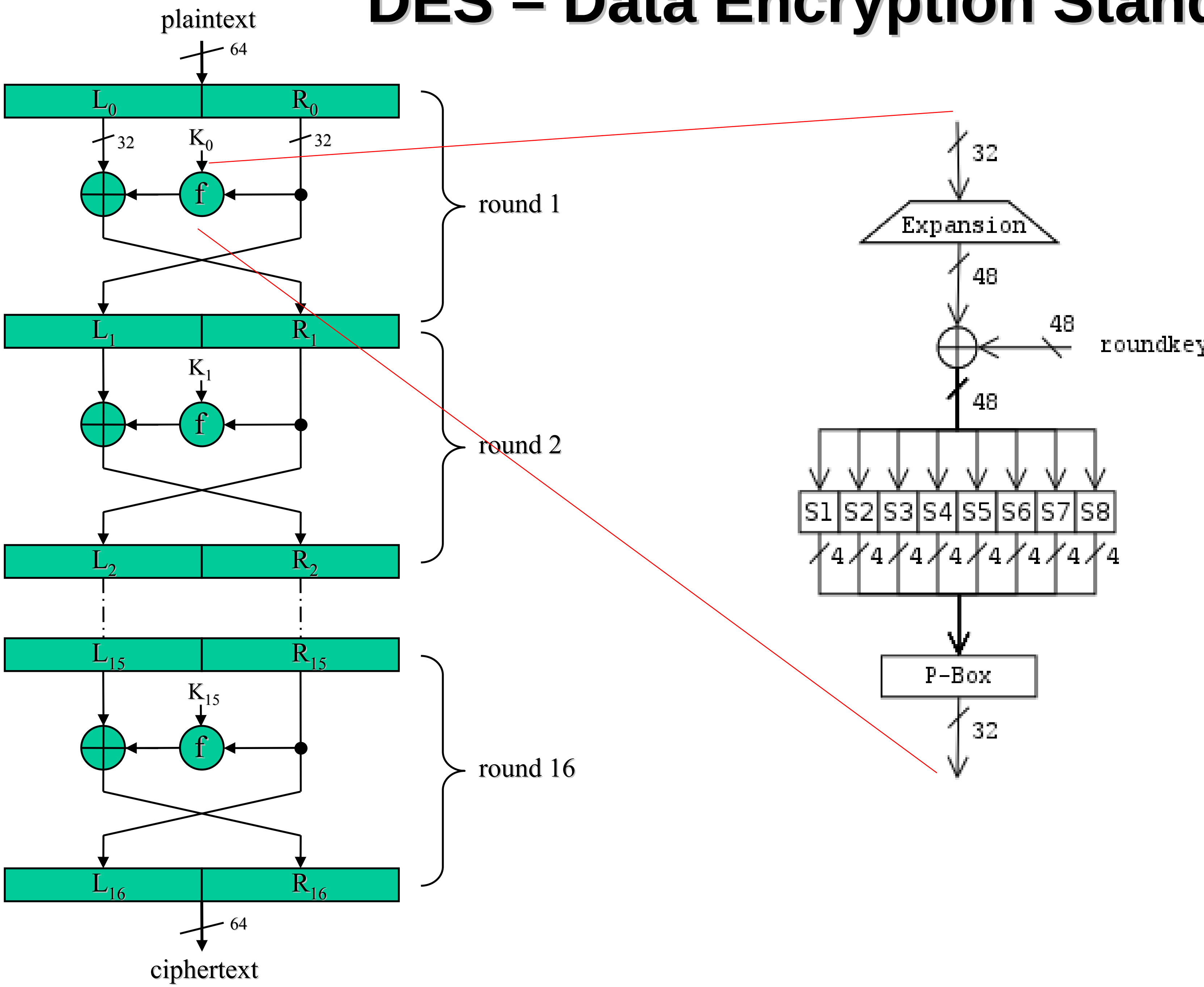
   $e_k(r) = y'$

   $y == y'$

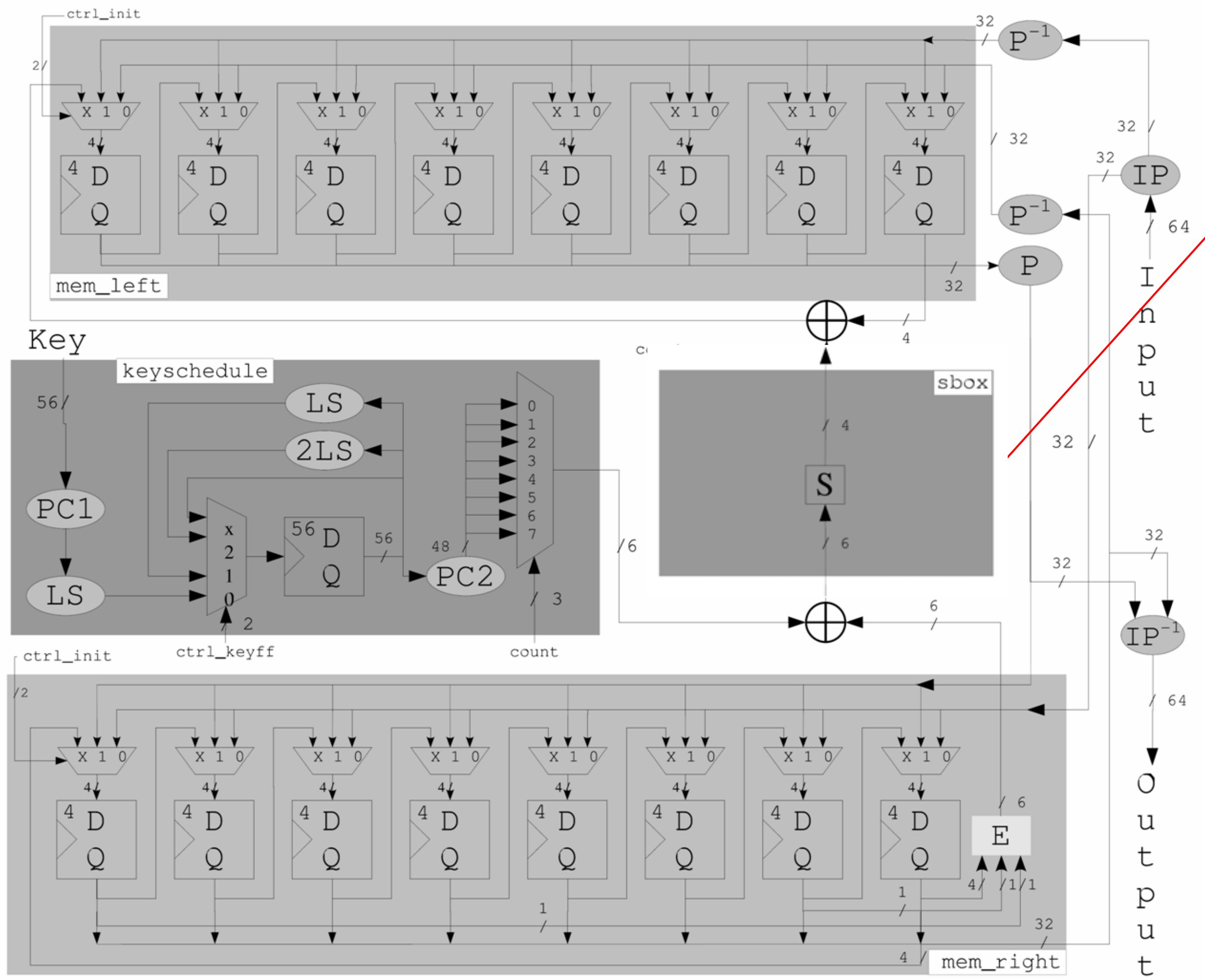
Challenge: Encryption function e() at extremely low cost

- almost all symmetric ciphers optimized with SW in mind
- exception: DES

DES – Data Encryption Standard

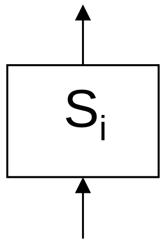


Serialized DES Architecture



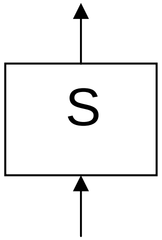
S-Boxes

- 4-to-6 substitution tables



- crucial for security
- highly non-linear
  → high Boolean compl.
- 32% of area!

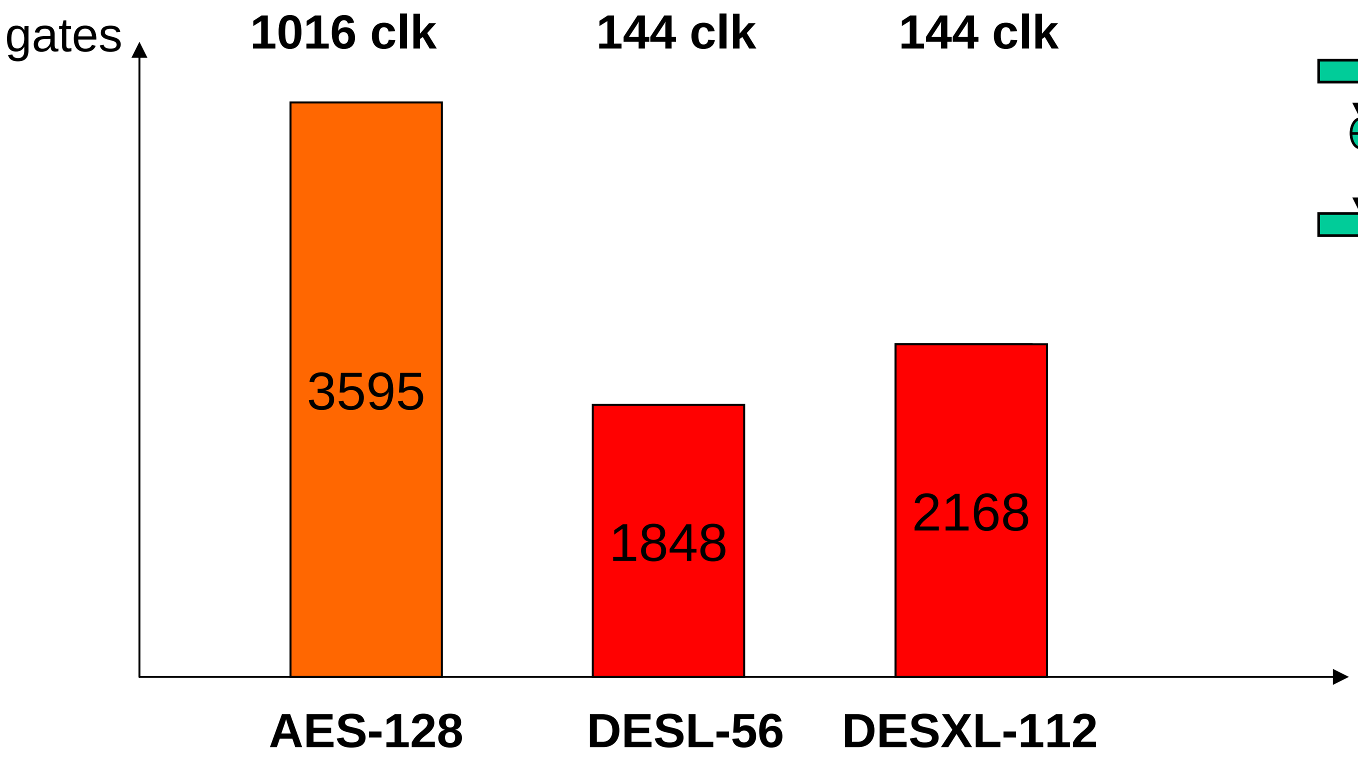
DESL: A Single S-Box DES Variant

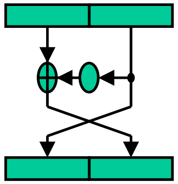


- DESL: replacing S1…S8 by S
- non-trivial problem
- no previous work (!)
- S must be robust against differential, linear, and David-Murphy attack
- New S more robust against known attacks than S1…S8

S															
14	5	7	2	11	8	1	15	0	10	9	4	6	13	12	3
5	0	8	15	14	3	2	12	11	7	6	9	13	4	1	10
4	9	2	14	8	7	13	0	10	12	15	1	5	11	3	6
9	6	15	5	3	8	4	11	7	1	12	2	0	14	10	13

Results – Light-Weight DES





- smallest known secure block cipher
- TA product 12-14 times better than smallest AES architecture
- only block cipher based on HW-optimum design

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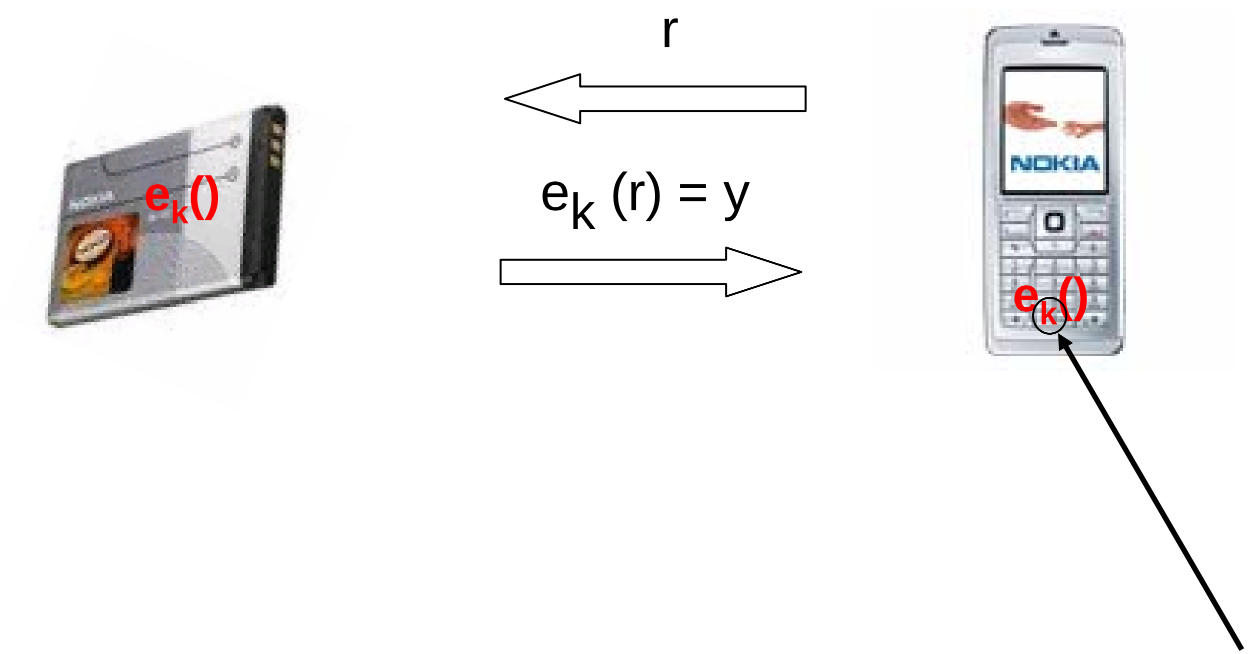
3. **Light-Weight Asymmetric Cryptography**

Strong Identification (w/ symmetric crypto)



Potential weakness: attacker gets access to key on host device

(e.g. firmware exploits) and starts cloning batteries

Strong Identification (w/ asymmetric crypto)

r

$sig_{kpr}(r) = y$

1. random challenge r
2. signed response y
3. verification
   $ver_{kpub}(r,y) = t/f$

Attacker can only access public key from host device

- But how cheap can we build public-key algorithms?
- Idea: use OTS 8bit μP (< $1)

Elliptic Curve Primitive

- Given a Point P on an elliptic curve E over GF(p):

$$E: \; y^2 = x^3 + ax + b \bmod p$$

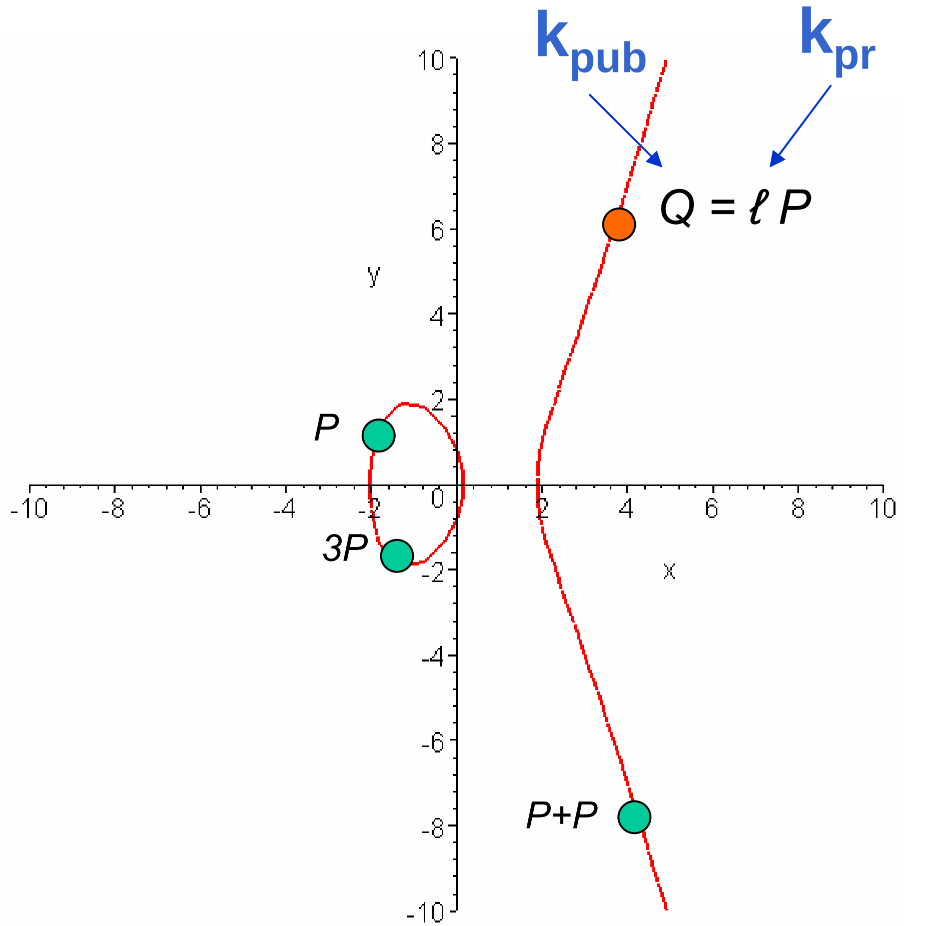
- Public key Q is multiple of base point P

group operation

$$Q = P+P+ \ldots +P = \ell P$$

- EC discrete logarithm problem:

$$\ell = dlog_P(Q)$$



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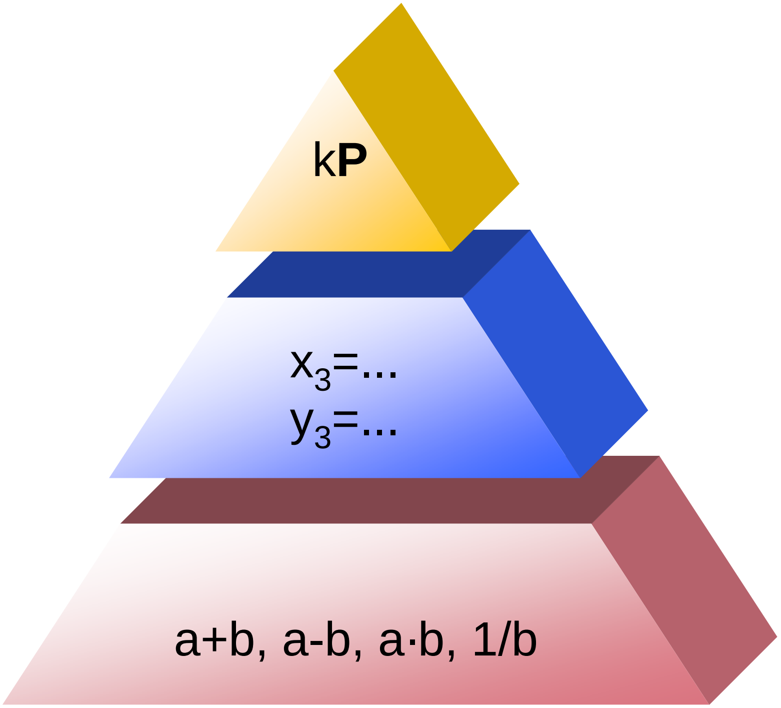
ECC System Design



- Protocol
  - Point Mult (k.**P**)
- Group Operation
  - Point Add/Double
- Field Operations
  - Addition/Subtraction
  - Multiplication
  - Reduction
  - Inverse

Design Principles for *Tiny ECC Processor*

- Reduce memory requirements

: memory amounts to more than 50% of design

- Reduce arithemtic unit area

: avoid units like inverter

+ designed for specific size

- Keep it simple but efficient

: reduce control logic area - multiplexers

Tiny ECC Processor Units

- Arithmetic Units
  - Multiplier – Most-Significant Bit Mult.
  - Squarer
  - inverter
- Point Multiplier
  - Control Unit
- Memory Unit

Most Significant Multiplier

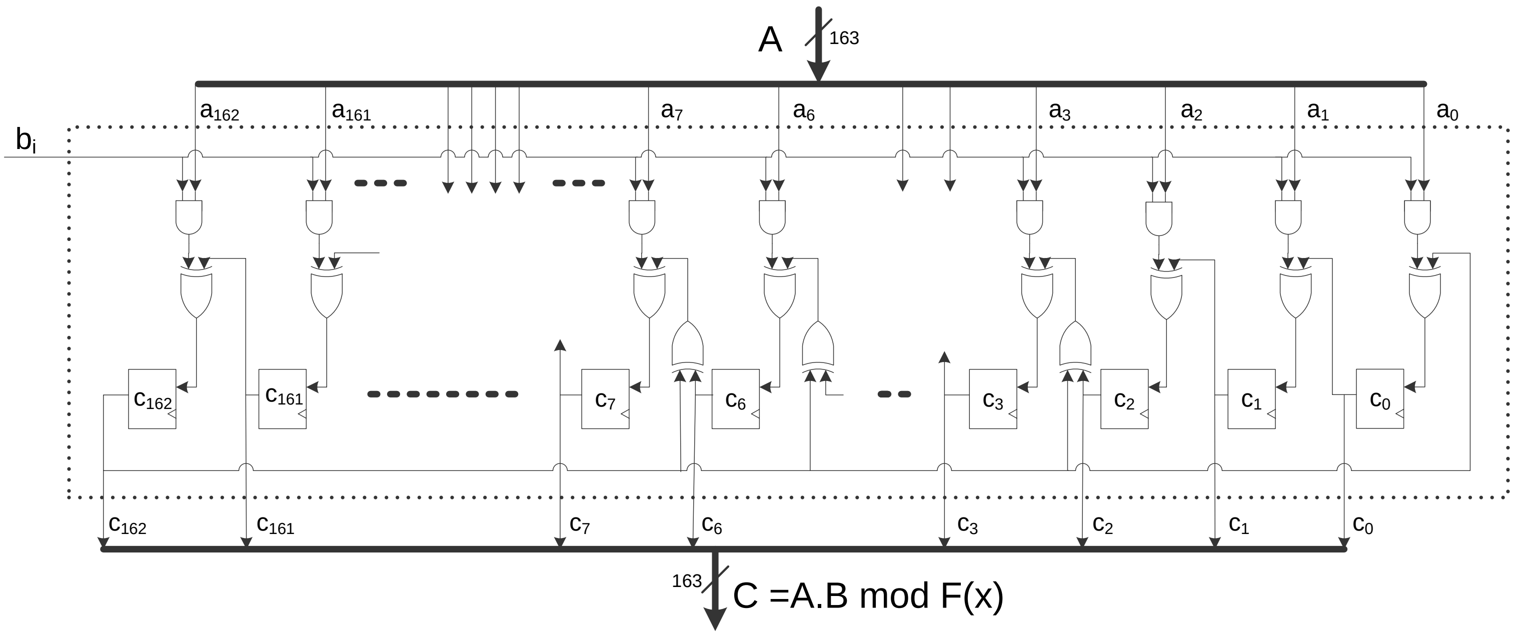
- $A, B \in GF(2^n)$
- $A(x) = a_{m-1}x^{m-1}+\cdots + a_1x+a_0$
- $C(x) = A(x) \times B(x)$

  $= A \times \sum b_i\, x^i \bmod F(x)$

  $=(\cdots(A \times b_{m-1}x + A \times b_{m-2})x\cdots)x+A \times b_0 \bmod F(x)$

The Implementation: MSB Multiplier

$$C(x)=A(x)\times B(x)=(\cdots(A\times b_{m-1}x + A\times b_{m-2})x\cdots)x+A\times b_0 \bmod F$$



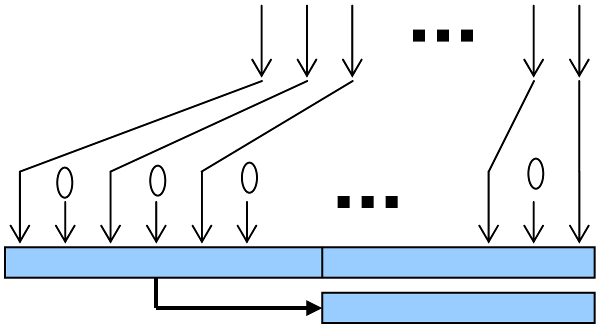
Most-Significant Bit (MSB) Multiplier: N cycles for n-bit multiplier

Tiny ECC Processor: Design decisions

- Arithmetic Units
  - Multiplier – Most-Significant Bit Mult.
  - Squarer – Parallel Squaring
  - inverter
- Point Multiplier
  - Control Unit
- Memory Unit

Squaring

- $A \in GF(2^n)$
- $A(x) = a_{m-1}x^{m-1} + \cdots + a_1x + a_0$
- $A^2(x) =$



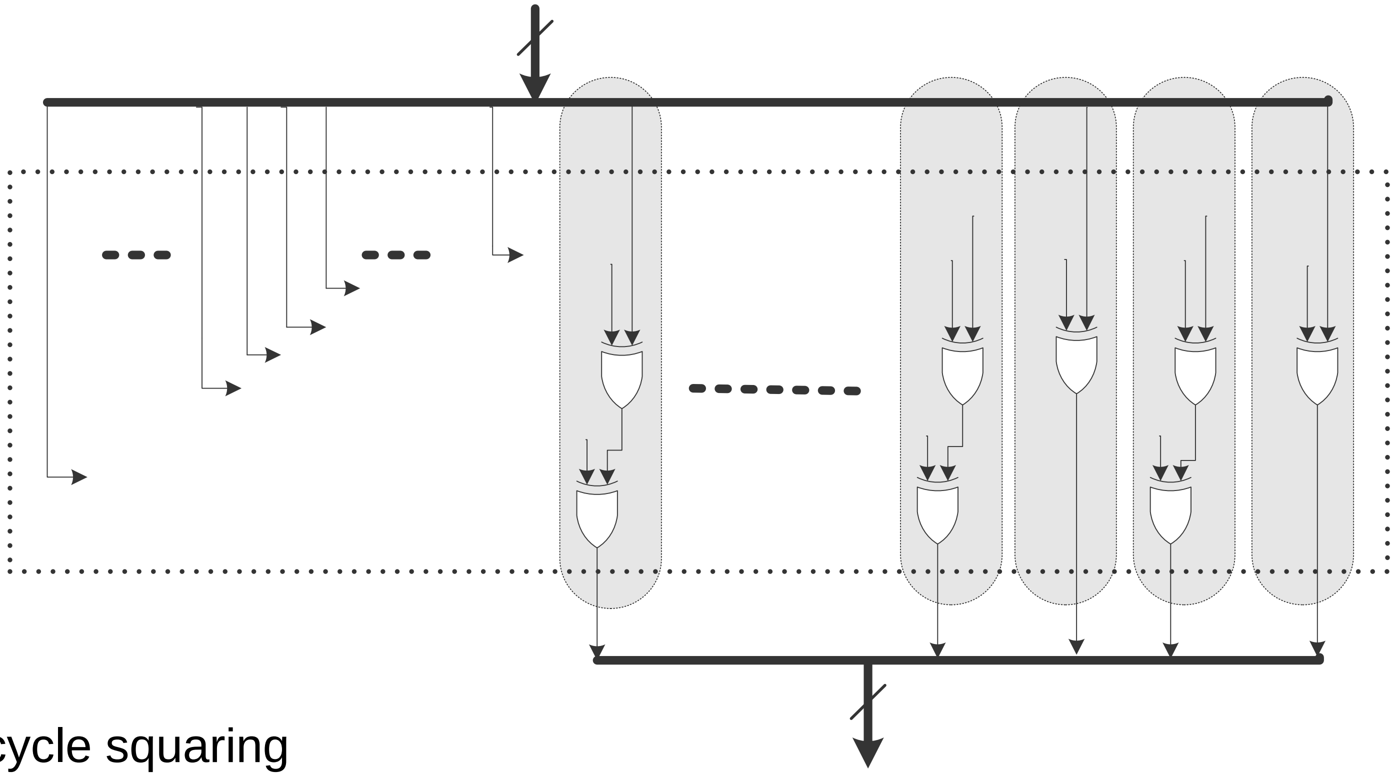
Step1: $a_{m-1}x^{2(m-1)} + \cdots + a_1x^2 + a_0$

Step2: $(a_{m-1}x^{2(m-1)} + \cdots + a_1x^2 + a_0) \bmod F(x)$

$= (a_{m-1}x^{2(m-1)} + \cdots + a_{m/2}x^m) \bmod F(x) +$

$(a_{m/2-1}x^{(m-2)} + \cdots + a_1x^2 + a_0)$

The Implementation: Squarer



- single cycle squaring
- low gate count
- low critical path

Tiny ECC Processor Units

- Arithmetic Units
  - Multiplier – Most-Significant Bit Mult.
  - Squarer – Parallel Squaring
  - inverter – Fermat's Little Theorem
- Point Multiplier
  - Control Unit
- Memory Unit

The Implementation: inverter

Fermat's Little Theorem

$A^{-1} \times A^{2^m-2} \bmod F(x)$ if $A \in GF(2^m)$

For m=163 : $A^{2^{163}-2}$
Straightforward exponentiation: 161 **Mult.** + 162 **Sqr.**

Exploit exponent structure:

Inversion using Itoh-Tsujii

$$A^{2^{163}-2} = A^{[\underbrace{111\cdots1}_{162}0]_2}$$

$$[\underbrace{111\cdots1}_{162}]_2 = [\underbrace{111\cdots1}_{81}]_2 \cdot 2^{81} + [\underbrace{111\cdots1}_{81}]_2$$

$$[\underbrace{111\cdots1}_{80}]_2 \cdot 2 + 1$$

$$[\underbrace{111\cdots1}_{40}]_2 \cdot 2^{40} + [\underbrace{111\cdots1}_{40}]_2$$

The Implementation: Inverter

Fermat's Little Theorem

$A^{-1} \times A^{2^m-2} \bmod F(x)$ if $A \in GF(2^m)$

For m=163 : $A^{2^{163}-2}$

Straightforward exponentiation: 161 **MUL** + 162 **SQ**

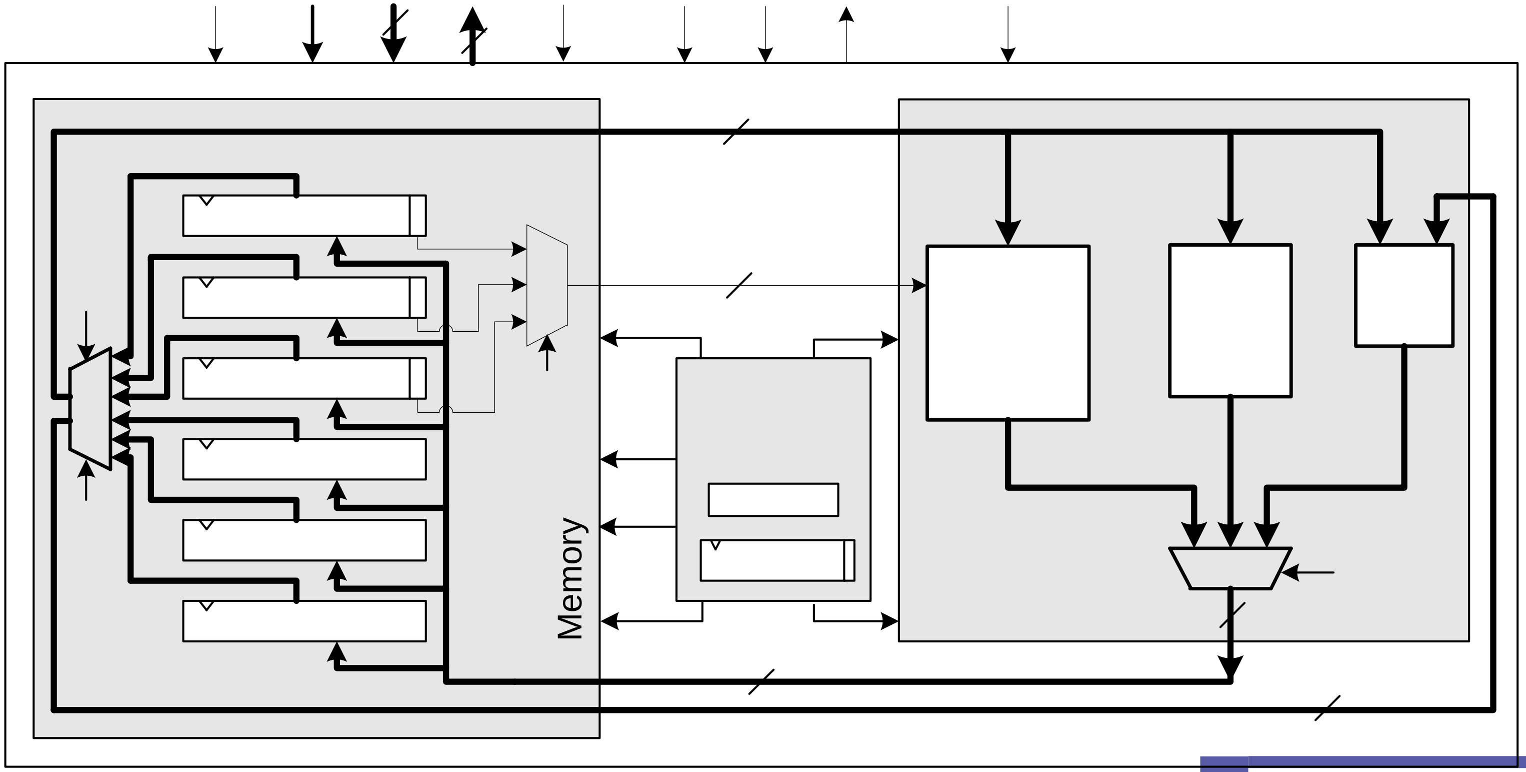
Exploit exponent structure:

$(\log_2(m-1) + HW(m-1) - 1)$ **MUL** + (m-1) **SQ**

For m=163: 9 **MUL** + 162 **SQ**

The Tiny ECC Processor Design

- ECC processor implementation for $2^{113}, 2^{131}, 2^{163}, 2^{193}$



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Performance and Results

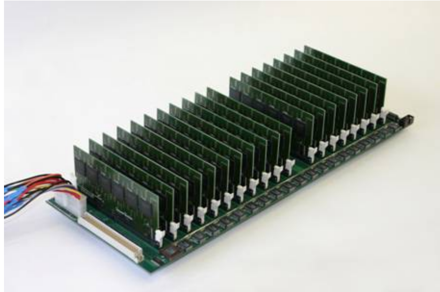
Performance @ 4 MHz for standardized curves

Field Size	**Arithmetic Unit**(gates)	**Memory** (gates)	**Total** (gates)	**Time** (ms)
113	1,625	6,686	**10,112**	**47**
131	2,071	7,747	**11,969**	**61**
163	2,572	9,632	**15,094**	**108**
193	2,776	11,400	**17,723**	**139**

131, 163 bit: very practical bit sizes

Security levels?

Security of mid-size ECC



Costs for breaking ECC in *one year* w/ optimized attack ASICs:

ECC131p $\approx$ \$2 million

ECC163p: $\approx$ \$1 trillion (> 20 years security)

cf [CHES06 & Jan Pelzl's talk at this workshop]

Related Workshops

escar – Embedded Security in Cars
November 2006, Berlin, Germany

SASC – Stream Ciphers Revisited
January 2007, Bochum, Germany

RFIDSec 2007
January 2007, Malaga, Spain

CHES – Cryptographic Hardware and Embedded Systems
September 2007, Vienna, Austria