Modes of Operations for Wide-Block Encryption

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Structure of Presentation

- From block cipher to wide block encryption.
- Construction Ideas.
- Sketches of several constructions.
- Comparative study.
Block Cipher

Definition. $E_K : \{0, 1\}^n \rightarrow \{0, 1\}^n$.

- $K \in \mathcal{K}$;
- for each $K$, $E_K$ is a permutation of $\{0, 1\}^n$;
- good practical examples are known, e.g. AES.
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- Resists “known” attacks.
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**Formal model.** A pseudo-random (unpredictable) permutation (Luby-Rackoff, 1985, 1988).
Pseudo-Random Permutation

\[ E_K \quad \pi \]

A
Pseudo-Random Permutation

\[
\text{Adv}^{\text{prp}}_E (\mathcal{A}) = \Pr_K [\mathcal{A}^{E_K} \to 1] - \Pr_\pi [\mathcal{A}^{\pi} \to 1].
\]
Strong PRP

\[ E_K \quad E_K^{-1} \quad \pi \quad \pi^{-1} \]
Strong PRP

\[
\text{Adv}_{E}^{\pm_{\text{prp}}}(A) = \Pr_{K}[A^{E_{K},E_{K}^{-1}} \rightarrow 1] - \Pr_{\pi}[A^{\pi,\pi^{-1}} \rightarrow 1].
\]
Tweakable Block Cipher

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\( E^T_K : \{0, 1\}^n \rightarrow \{0, 1\}^n. \)

- \( K \) is the secret key;
- \( T \in T \) is the tweak;
- for each \((K, T)\) pair \( E^T_K \) is a permutation of \( \{0, 1\}^n \);
Tweakable Block Cipher


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Tweakable (S)PRP.

- The tweak (unlike the key) is assumed to be known to the adversary.
- In its queries, the adversary can
  - choose a tweak;
  - reuse a tweak (with another message).
Modes of Operations

A block cipher can encrypt short and fixed length strings.
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Applications require the encryption of long strings of possibly different lengths.
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Applications have different goals.

- Privacy.
- Authentication.
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A mode of operation is used to extend the capabilities of a block cipher to achieve a desired goal.
Length Preserving Encryption

The set of messages $\mathcal{M}$ consists of strings of different lengths.
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The length of the ciphertext should be equal to the length of the message.
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The length of the ciphertext should be equal to the length of the message.

Security: a natural extension of the notion of (S)PRP defined for a block cipher.

Real oracle: is the actual encryption.

Random oracle: is a uniform random length preserving permutation of $\mathcal{M}$.
Wide Block Encryption

- A length preserving mode of operation.
- Supports a tweak.
- Other names.
  - Tweakable enciphering scheme.
  - Tweakable strong pseudo-random permutation.
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Disk encryption.

- Encryption is done sector-wise.
- Sector address is the tweak.
Construction Ideas
Types of Constructions

Hash-Encrypt-Hash.
• Introduced by Naor-Reingold (1999);
• later work done by several other authors.

Encrypt-Mix-Encrypt
• Introduced by Halevi-Rogaway (2003);
• followed up by Halevi-Rogaway (2004);
• and Halevi (2004).
Hash-Encrypt-Hash

Encryption layer is ECB.

- NRmode (Naor-Reingold 1999);
- PEP (Chakraborty-Sarkar 2005);
- TET (Halevi 2007);
- HEH (Sarkar 2007).
Hash-Encrypt-Hash

Encryption layer is Ctr.

• XCB (McGrew-Fluhrer 2004);
• HCTR (Wang-Feng-Wu 2005);
• HCH (Chakraborty-Sarkar 2006);
• iHCH (Sarkar 2008).
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Encryption layers are CBC.

• CMC (Halevi-Rogaway 2003)
Encrypt-Mix-Encrypt

Encryption layers are CBC.

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Encryption layers are ECB.

- EME/EME\(^+\) (Halevi-Rogaway 2004);
- EME\(^*\) (Halevi 2004)
- EMME (Sarkar 2008): generalises the masking operations of EME and its variants; no change in structure of the constructions.
Overview of Constructions

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Analysis is information theoretic. Consequently, adversary can be assumed to be deterministic.
Time bounded probabilistic adversary and computational complexity theoretic analysis required to tackle the replacement of $E_K$ by $\pi$. 
Overview of Constructions

If the inputs to $\pi$ and $\pi^{-1}$ are distinct, then their outputs are almost uniformly distributed.
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Crux. Prove that with high probability the inputs to $\pi$ and $\pi^{-1}$ are distinct.

- In the hash-encrypt-hash approach, a universal hash function is required to ensure this.
- In the encrypt-mix-encrypt approach, an implicit universal hash is built.
Universal Hash Definition

Function family.
Fix integer $m \geq 1$ and let $\mathbb{F}$ be a finite field.

$$\mathcal{F} : \mathcal{K} \times \mathbb{F}^m \rightarrow \mathbb{F}.$$
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Fix integer $m \geq 1$ and let $\mathbb{F}$ be a finite field.

$$\mathcal{F} : \mathcal{K} \times \mathbb{F}^m \to \mathbb{F}.$$ 

$\epsilon$-almost universal ($\epsilon$-AU):
For $x, x' \in \mathbb{F}^m, x \neq x'$,

$$\Pr_{K}[\mathcal{F}_K(x) = \mathcal{F}_K(x')] \leq \epsilon.$$ 

In other words, the collision probabilities are small.
Universal Hashing

$$\mathcal{F}_K(P_1, \ldots, P_m) = P_m + KP_{m-1} + \cdots + K^{m-1}P_1.$$
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Requires \((m - 1)\) multiplications; \(m/|\mathbb{F}|\)-AU; \(K \mathcal{F}_K\) satisfies XOR universality.
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Bernstein (2007): introduces a class of polynomials which builds upon earlier work by Rabin-Winograd; BRW polynomials can be computed using \(m/2\) multiplications; \(2m/|\mathbb{F}|\)-AU;
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Sarkar (2008): universal hashing from word oriented LFSRs; no multiplications; bitwise processing – slow in software; good for resource constrained devices.
Invertible Blockwise Universal

Fix integer $m \geq 1$ and let $\mathbb{F}$ be a finite field.

$$\mathcal{F} : \mathcal{K} \times \mathbb{F}^m \rightarrow \mathbb{F}^m$$

- For each $K \in \mathcal{K}$, $\mathcal{F}_K$ is invertible.
- $(x, i) \neq (x', i')$, $1 \leq i, i' \leq m$. 
Invertible Blockwise Universal

Fix integer \( m \geq 1 \) and let \( \mathbb{F} \) be a finite field.

\[ \mathcal{F} : \mathcal{K} \times \mathbb{F}^m \to \mathbb{F}^m \]

- For each \( K \in \mathcal{K} \), \( \mathcal{F}_K \) is invertible.
- \( (x, i) \neq (x', i'), 1 \leq i, i' \leq m \).

\( \epsilon \)-BAU.

\[ \mathcal{F}_K : (X_1, \ldots, X_m) \mapsto (Y_1, \ldots, Y_m) \]
\[ \mathcal{F}_K : (X'_1, \ldots, X'_m) \mapsto (Y'_1, \ldots, Y'_m) \]

\[ \Pr_{K}[Y_i = Y'_{i'}] \leq \epsilon. \]
Constructions

\((X_1, \ldots, X_m) \mapsto\)

- \((X_1 \oplus u(Y), \ldots, X_{m-1} \oplus u(Y), Y) \oplus (\phi_\beta(0), \ldots, \phi_\beta(m - 1))\) (NR 99)

- \((X_1 \oplus Y, \ldots, X_{m-1} \oplus Y, Y) \oplus (\phi_\beta(0), \ldots, \phi_\beta(m - 1))\) (Sarkar 08)

\[ Y = X_m \oplus \psi_\tau(X_1, \ldots, X_{m-1}); \phi, \psi \text{ and } u \text{ are AXU;} \]
Constructions

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$$Y = X_m \oplus \psi_\tau(X_1, \ldots, X_{m-1}); \ \phi, \psi \text{ and } u \text{ are AXU; }$$

$$(X_1, \ldots, X_m) \mapsto$$

- $$(X_1 \oplus Z, \ldots, X_m \oplus Z) \oplus (\beta, \alpha\beta, \ldots, \alpha^{m-1}\beta) \ (\text{Halevi 07})$$

$$Z = \sigma^{-1}(X_1\tau^m \oplus \cdots \oplus X_{m-1}\tau^2 \oplus X_m\tau); \ \sigma = 1 \oplus \tau \oplus \cdots \oplus \tau^m.$$
Hash-ECB-Hash Constructions
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$H$ and $G$ are invertible blockwise universal hash functions.
Hash-ECB-Hash Constructions

NRmode. Predates the notion of tweaks; did not specify handling of partial blocks.
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TET. Incorporates tweaks and handles partial blocks. But, more complicated and hence less efficient.
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HEH. Incorporates tweaks and handles partial blocks. Simplifies NRmode construction; more efficient than TET.
Hash-ECB-Hash Constructions

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HEH. Incorporates tweaks and handles partial blocks. Simplifies NRmode construction; more efficient than TET.

Other less efficient constructions known.
HEH (Full Blocks)

\[ H_{K_1} = \Psi_{\tau, \beta_1}, \quad G_{K_2} = \Psi_{\tau, \beta_2}. \]
HEH (Full Blocks)

\[ H_{K_1} = \Psi_{\tau, \beta_1}, \quad G_{K_2} = \Psi_{\tau, \beta_2}. \]

\[ \Psi_{\tau, \beta}(X_1, \ldots, X_m) = (X_1 \oplus Y, \ldots, X_{m-1} \oplus Y, Y) \oplus (\phi_\beta(1), \ldots, \phi_\beta(m - 1), \phi_\beta(0)) \]

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\[ Y = X_m \oplus \psi_{\tau}(X_1, \ldots, X_{m-1}). \]
\[ \phi_{\beta} : i \mapsto \alpha^i \beta; \alpha \text{ is a primitive element of } GF(2^n). \]
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\[ Y = X_m \oplus \psi_{\tau}(X_1, \ldots, X_{m-1}). \]

\[ \phi_{\beta} : i \mapsto \alpha^i \beta; \ \alpha \text{ is a primitive element of } GF(2^n). \]

\[ \psi_{\tau} \text{ can be instantiated using} \]

- usual polynomial hashing;
- hashing using BRW polynomials;
- hashing using word oriented LFSRs.
HEH (Partial Block)

Handling partial blocks.
HEH (Partial Block)

\[ \Phi_{\tau, \beta}(X_1, \ldots, X_{m-1}, X_m) = (X_1 \oplus Y, \ldots, X_{m-2} \oplus Y, Y, X_m) \oplus (\phi_{\beta}(1), \ldots, \phi_{\beta}(m-2), \phi_{\beta}(0), 0^r) \]

\[ Y = X_{m-1} \oplus \psi_{\tau}(X_1, \ldots, X_{m-2}, X_m || 0^{n-r}) \]

Note.

- \( X_{m-1} \) is the last full block;
- \( \phi_{\beta} \) and \( \psi_{\tau} \) defined as for full blocks.
## Definition of \( \tau, \beta_1, \beta_2 \)

<table>
<thead>
<tr>
<th>KeyDef1</th>
<th>KeyDef2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma = E_K(T) ); ( \beta_1 = E_K(\gamma \oplus \text{bin}_n(\ell)) ); ( \beta_2 = \alpha \beta_1 ); ( \tau = \gamma ).</td>
<td>( \gamma = E_K(T) ); ( \beta_1 = E_K(\gamma \oplus \text{bin}_n(\ell)) ); ( \beta_2 = \alpha \beta_1 ); choose ( \tau ) randomly from ( GF(2^n) ).</td>
</tr>
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</table>

| KeyDef3 | |
|---------| |
| \( \beta_1 = E_K(T) \); \( \beta_2 = \alpha \beta_1 \); choose \( \tau \) randomly from \( GF(2^n) \). | |

**KeyDef1**: single key; no pre-comp;  
**KeyDef2**: separate hash key; allows pre-comp;  
**KeyDef3**: fixed length; saves one call.
Counter/OFB Based Constructions
XCB Mode of Operation
HCtr Mode of Operation

Diagram:

- $P_1$ is connected to $E_K$, then to $H_h$, and finally to $Ctr_K$.
- $P_2$ is connected to $T$, then to $H_h$, and finally to $Ctr_K$.
- $P_m$ is connected directly to $Ctr_K$.
- $C_1$ is connected to $E_K$ and then to $H_h$.
- $C_2$ is connected to $T$ and then to $H_h$.
- $C_m$ is connected directly to $Ctr_K$.
HCH Mode of Operation

\[ P_1 \rightarrow \oplus \rightarrow E_K \rightarrow \oplus \rightarrow H_{R,Q} \rightarrow \cdots \rightarrow Ctr_K \rightarrow \cdots \]

\[ S \rightarrow E_K \rightarrow \oplus \rightarrow H_{R,xQ} \rightarrow \cdots \rightarrow \]

\[ C_1 \rightarrow \cdots \rightarrow C_m \]

\[ P_2, P_m \rightarrow \cdots \]

Wide-Block Encryption – p. 31/45
iHCH/HOH Modes

\[ \text{Mode}_{K, \beta_1, \beta_2, S} \]

\[ H_{\tau, \beta_1} \]

\[ H_{\tau, \beta_2} \]

\[ E_K \]

\[ M_1 \]

\[ U_1 \]

\[ P_1 \]

\[ P_2 \]

\[ P_m \]

\[ C_1 \]

\[ C_2 \]

\[ C_m \]
iHCH/HOH Modes

\[ H_{\tau, \beta}(X_1, \ldots, X_m) = \beta \oplus X_1 \oplus \psi_{\tau}(X_2, \ldots, X_m). \]

Mode \( K, \beta_1, \beta_2, S \) as Counter:

\[ \text{Ctr}_{K, \beta_1, R}(X_1, \ldots, X_m) = \text{ECB}_K(R_1, \ldots, R_m) \]

where \( R = S \oplus \beta_1 \oplus \beta_2, R_i = \phi_{\beta}(i - 1) \oplus R. \)

Mode \( K, \beta_1, \beta_2, S \) as OFB:

\[ \text{OFB}_{K, S}(X_1, \ldots, X_m) = (X_1, \ldots, X_m) \oplus (S_1, \ldots, S_m) \]

where \( S_i = E^i_K(S); \beta_1 \) and \( \beta_2 \) are not used.
Encrypt-Mix-Encrypt Constructions
$SP = PPP_2 \oplus PPP_3 \oplus PPP_4$; $SC = CCC_2 \oplus CCC_3 \oplus CCC_4$; $M = MP \oplus MC$. 

Wide-Block Encryption – p. 35/45
EMME Mode of Operation

\[ SP = PPP_2 \oplus PPP_3 \oplus PPP_4; \quad SC = CCC_2 \oplus CCC_3 \oplus CCC_4; \quad M = MP \oplus MC. \]
EMME Mode of Operation

EME: “Multiplication by $x$”: $S \rightarrow xS \mod \tau(x)$

$\tau(x)$: primitive, degree $n$ polynomial over $GF(2)$. 

Wide-Block Encryption – p. 37/45
EMME Mode of Operation

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EMME: Generalization: $\psi : GF(2^n) \rightarrow GF(2^n)$; linear map whose minimal polynomial over $GF(2)$ is primitive and of degree $n$. 
EMME Mode of Operation

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EMME: Generalization: \( \psi : GF(2^n) \to GF(2^n) \);
linear map whose minimal polynomial over \( GF(2) \) is primitive and of degree \( n \).

- \( \psi \) can be instantiated using a tower field representation of \( GF(2^n) \);
- “word oriented LFSR”;
- software implementation is faster than “multiplication by \( x \)”. 
Comparison Issues

Security: all modes provide the same security level.
Efficiency:
• Number of block cipher calls.
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- Number of other key material (if any).
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- Use of pre-computed multiplication tables (if relevant).
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- Parallelism, simplicity, ...
- An important issue: Variable/arbitrary versus fixed length messages.
### Variable Length – Efficiency

<table>
<thead>
<tr>
<th>Mode</th>
<th>([\text{BC}])</th>
<th>([\text{M}])</th>
<th>([\text{I}])</th>
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<tbody>
<tr>
<td>EME*</td>
<td>(2m + m/n + 1)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>XCB</td>
<td>((m + 6))</td>
<td>(2(m + 1))</td>
<td>–</td>
</tr>
<tr>
<td>HCTR</td>
<td>(m)</td>
<td>(2(m + 1))</td>
<td>–</td>
</tr>
<tr>
<td>HCH</td>
<td>((m + 3))</td>
<td>(2(m - 1))</td>
<td>–</td>
</tr>
<tr>
<td>TET</td>
<td>(2\iota + m + 2)</td>
<td>(\iota(m - 1) + 2m)</td>
<td>1</td>
</tr>
<tr>
<td>XXX</td>
<td>((m + 2))</td>
<td>(2(m - 1))</td>
<td>–</td>
</tr>
<tr>
<td>XXX</td>
<td>((m + 2))</td>
<td>(m \text{ (with BRW)})</td>
<td>–</td>
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</table>

**XXX**: HEH, iHCH, HOH; for TET \(\iota \geq 1\).
## Variable Length – # Keys

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<td>EME*</td>
<td>1[BCK] + 2[AK]</td>
</tr>
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<td>1[BCK]</td>
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</tr>
<tr>
<td>XXX</td>
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## Fixed Length Messages

<table>
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<th>[BCK]</th>
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<tbody>
<tr>
<td>EME*</td>
<td>(2m + 1 + m/n)</td>
<td>–</td>
<td>1</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td>XCB</td>
<td>(m + 1)</td>
<td>(2(m + 3))</td>
<td>3</td>
<td>2</td>
<td>yes</td>
</tr>
<tr>
<td>HCTR</td>
<td>(m)</td>
<td>(2(m + 1))</td>
<td>1</td>
<td>1</td>
<td>yes</td>
</tr>
<tr>
<td>HCH</td>
<td>(m + 2)</td>
<td>(2(m - 1))</td>
<td>1</td>
<td>1</td>
<td>yes</td>
</tr>
<tr>
<td>TET</td>
<td>(m + 1)</td>
<td>(2m)</td>
<td>2</td>
<td>3</td>
<td>yes</td>
</tr>
<tr>
<td>XXXX</td>
<td>(m + 1)</td>
<td>(2(m - 1))</td>
<td>1</td>
<td>1</td>
<td>yes</td>
</tr>
<tr>
<td>XXXX</td>
<td>(m + 1)</td>
<td>(m) (BRW)</td>
<td>1</td>
<td>1</td>
<td>no</td>
</tr>
</tbody>
</table>

XXX: HEH, iHCH, HOH.
# Key Agility

<table>
<thead>
<tr>
<th>Mode</th>
<th>comp. cost</th>
<th>key sch.</th>
<th>mult. tab.</th>
</tr>
</thead>
<tbody>
<tr>
<td>EME*</td>
<td>–</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>XCB</td>
<td>5[BC]</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>HCTR</td>
<td>–</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>HCH</td>
<td>–</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>TET</td>
<td>(\nu((m - 1)[M] + 1[BC]))</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>XXX</td>
<td>–</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

XXX: HEH, iHCH, HOH.
Comparison Summary

Software implementation:

- HOH will be the fastest: there are no masking operations; HEH, iHCH are also good choices;
- so are HCTR and HCH;
- XCB has good efficiency but less efficient key agility;
- TET: inefficient for variable lengths; bad key agility for fixed lengths.
- EME is good; EMME is slightly better.
- No pre-computation: use BRW polynomials.
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- EME is good; EMME is slightly better.
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**Hardware implementation:**

- Issues: chip size, memory, ...
- HEH, iHCH, HOH offer the best features.
Patents and Standards

**Patented:** EME/EME*, XCB.

**Unpatented:**
- NRmode, TET, HEH;
- HCtr, HCH, iHCH (uses Ctr mode; as does XCB).
- HOH.

**IEEE P1619.2 standard:** decision (as of Nov 2008) to standardize
- EME2 (of the encrypt-mix-encrypt type)
- XCB (of the hash-encrypt-hash type)

https://siswg.net/
Thank you for your attention!