Algebraic Pseudorandom Functions with Improved Efficiency from Augmented Cascade

Dan Boneh
Hart Montgomery
Ananth Raghunathan

Stanford University

Pseudorandom Functions

- Definition

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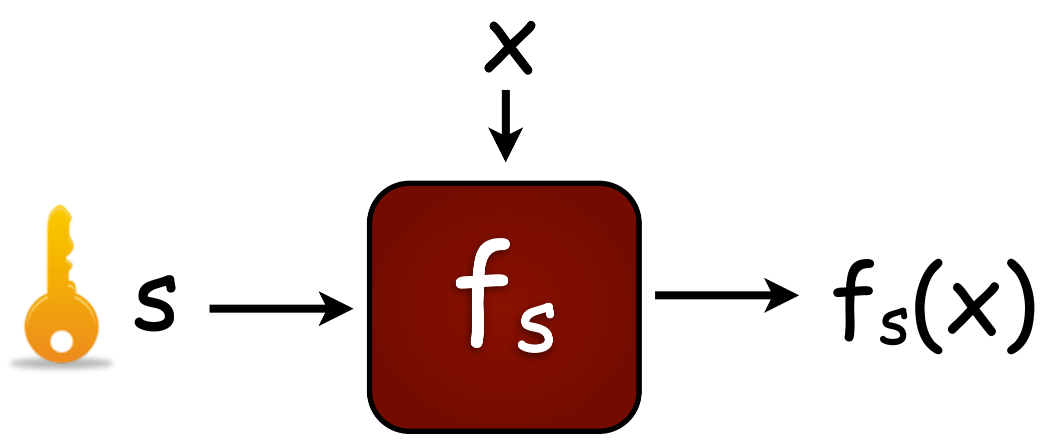

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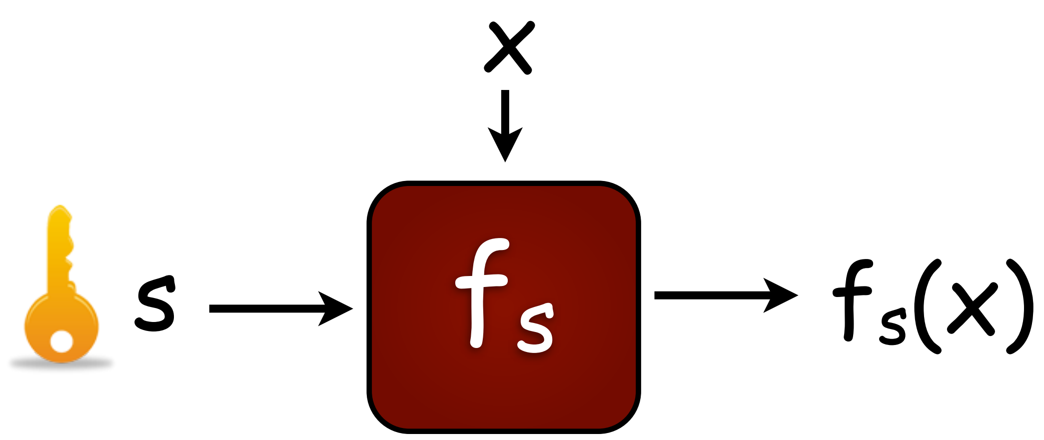

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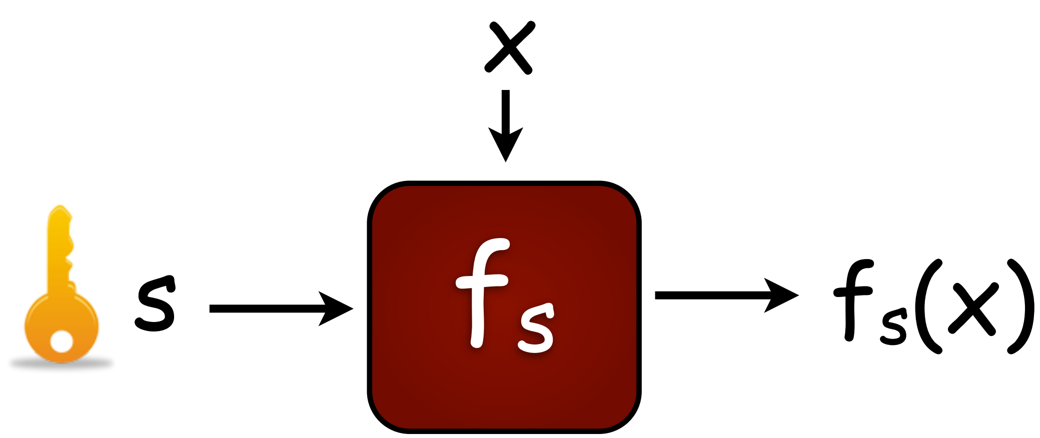

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Exp-PRF: choose a random key k and set $f(x)=f_k(x)$

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$$\xleftarrow{\;x\;}$$
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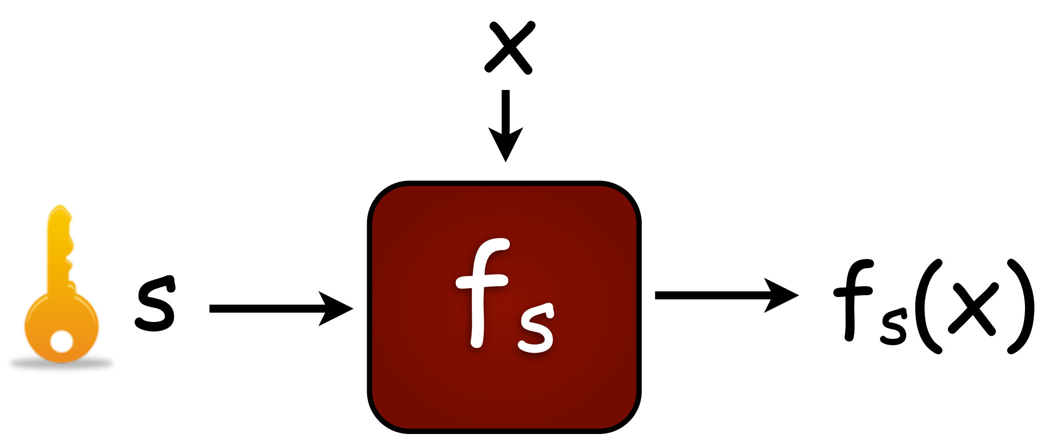

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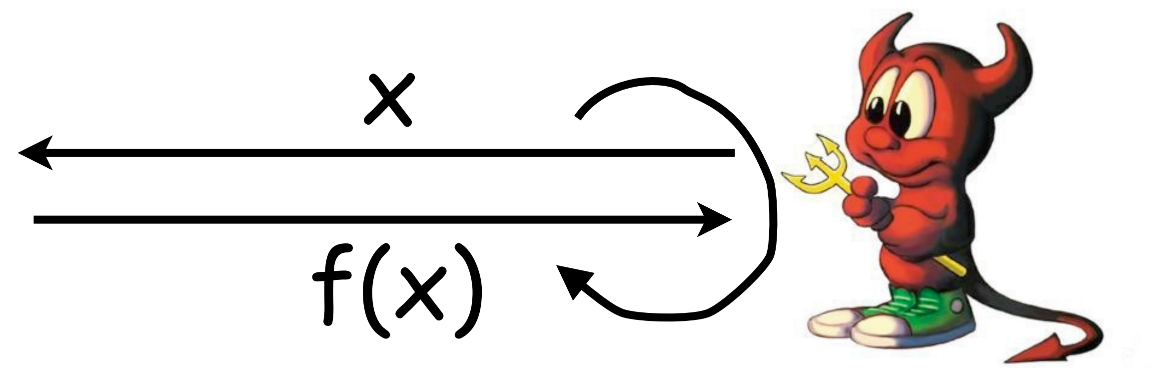

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$f(x)$

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PRF? or rand?

Secure if  cannot guess "PRF" or "rand" with probability better than 1/2

Applications of PRFs

- Workhorse of cryptography. Lots of applications!
  - Private Key Crypto; parties share PRF secret
  - Message Integrity and User Authentication
  - Key Derivation schemes
  - Stateless Signature Schemes
  - Defend against denial-of-service attacks [Ber ’96, CW03]
  - Prove lower bounds in learning theory; impossibility results in complexity theory

Heuristic PRFs

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DES IDEA **AES**
Triple-DES Serpent

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Algebraic Constructions

Non-interactive assumptions: Challenges posted. Require no interaction.

Eg., DDH, Discrete Log, etc.

Cascade Construction

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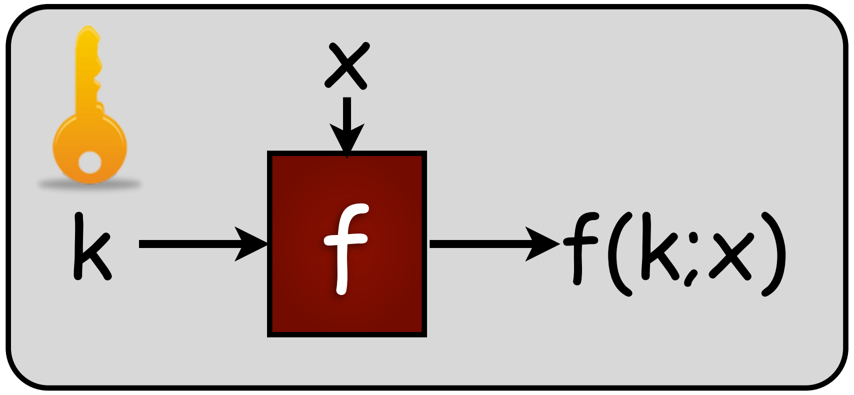
$$f : K \times X \rightarrow K$$



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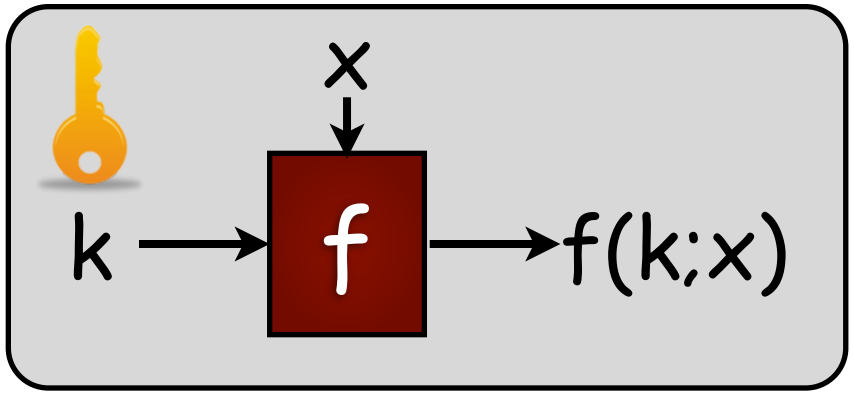

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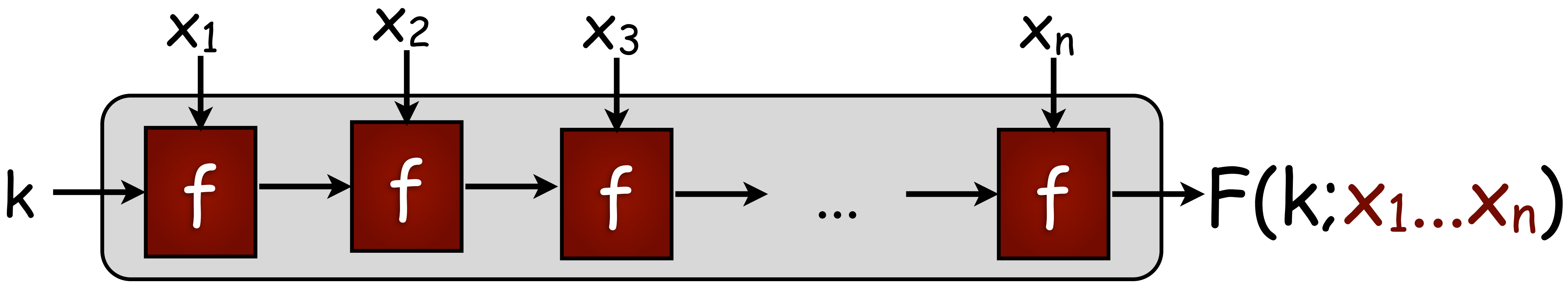

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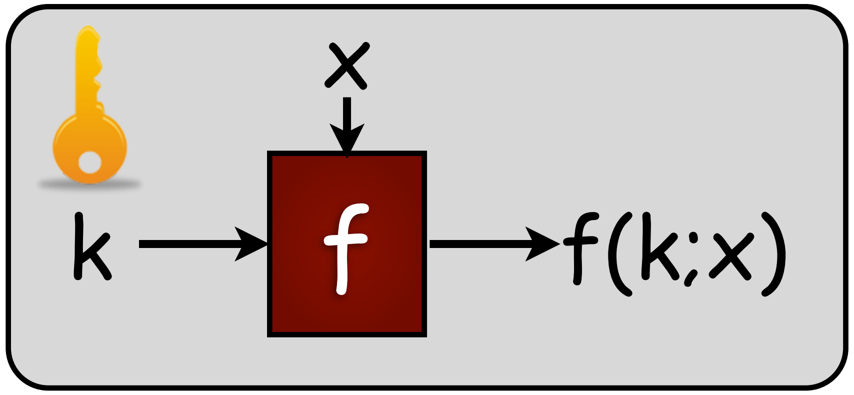

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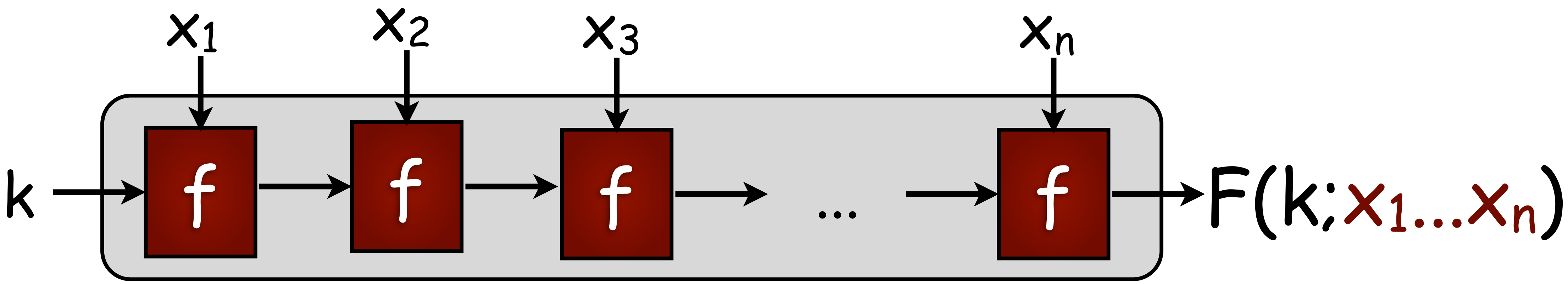

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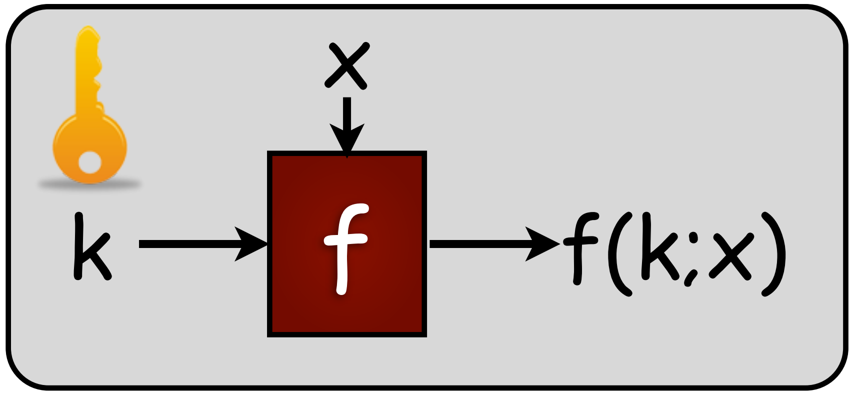

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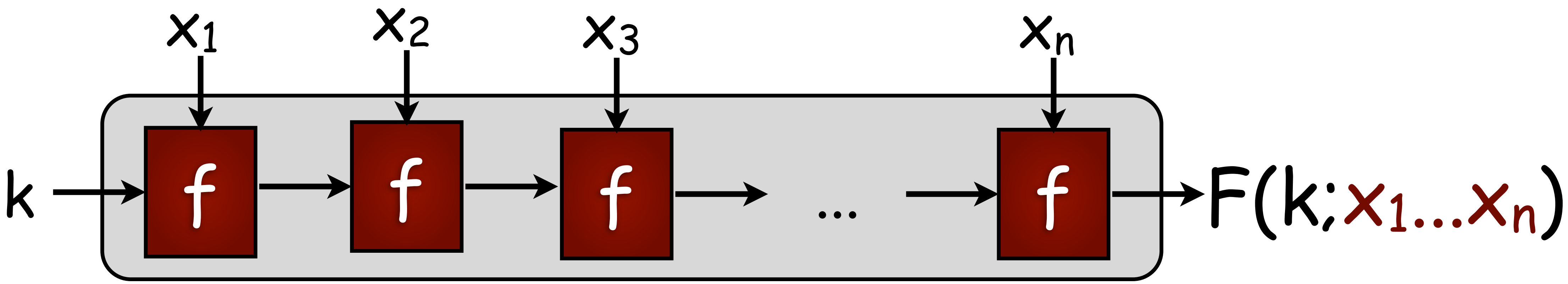

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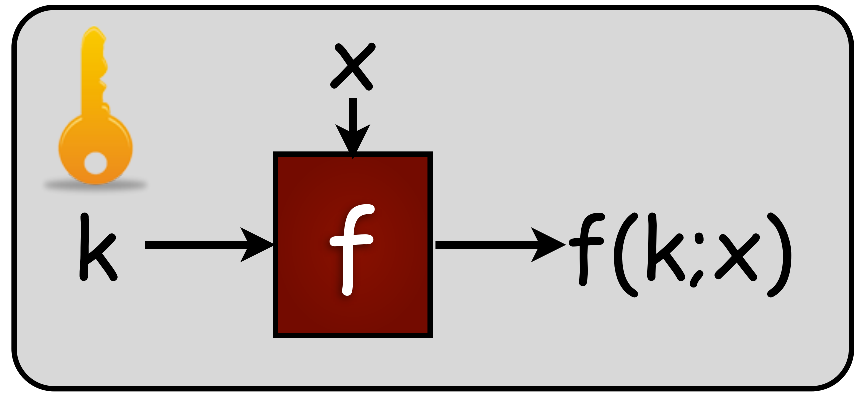

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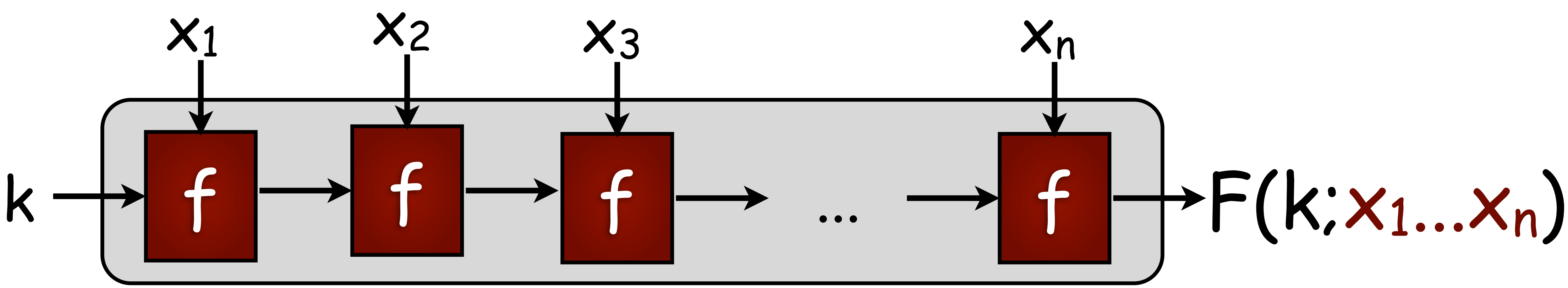

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Generalizes first algebraic construction of PRF by Goldreich-Goldwasser-Micali [GGM '86] from Pseudorandom Generators

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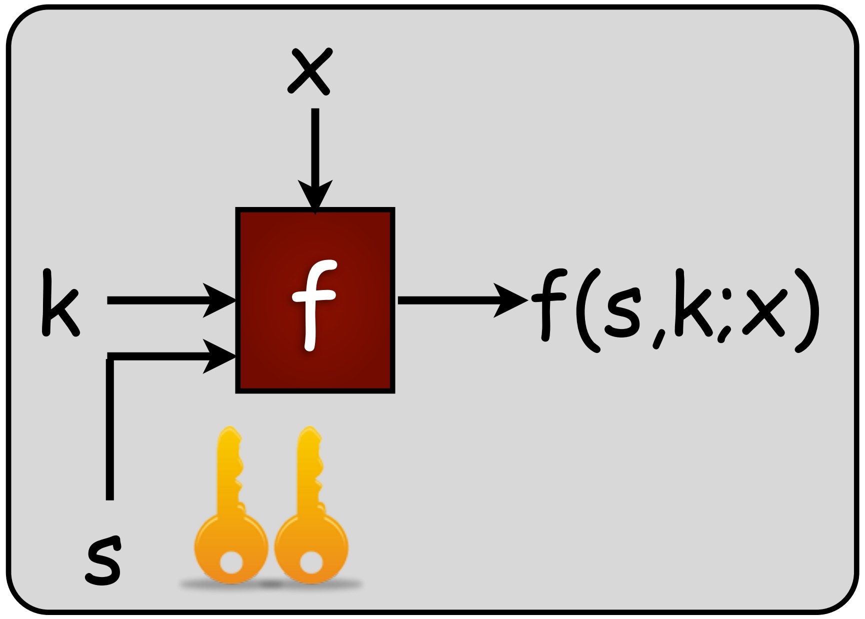

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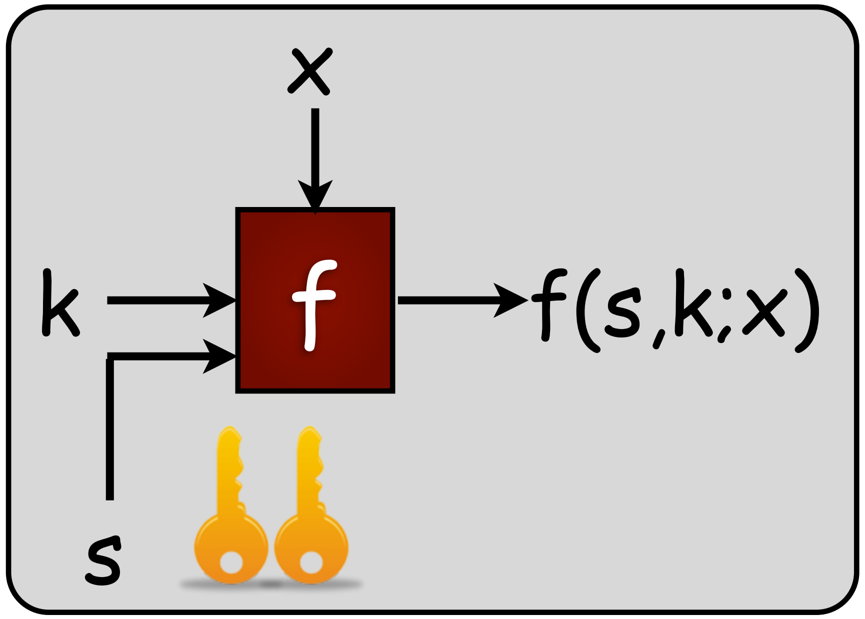

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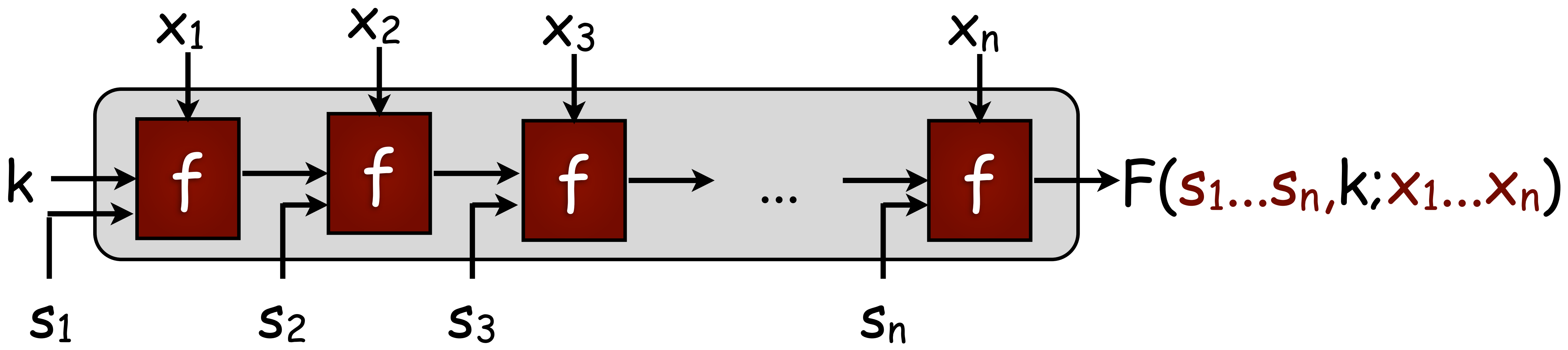

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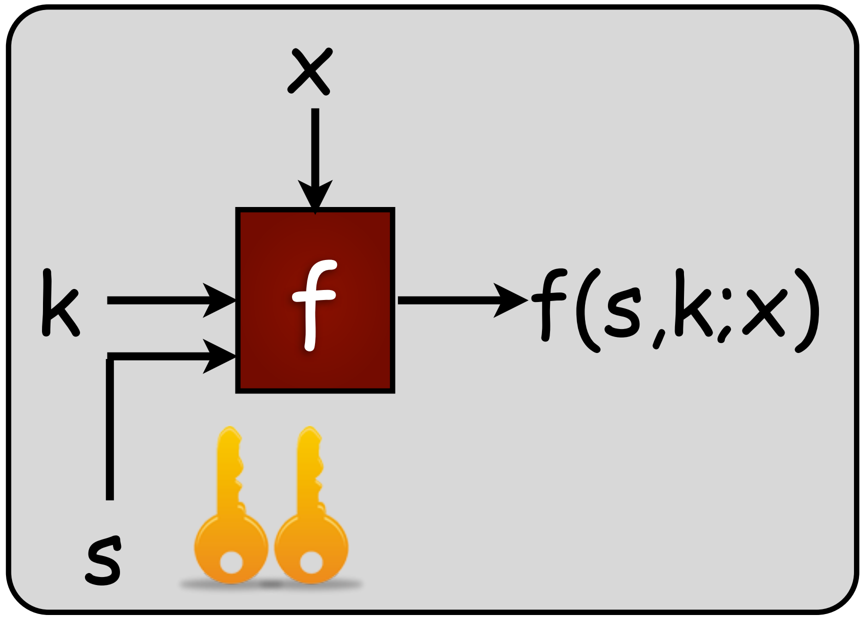

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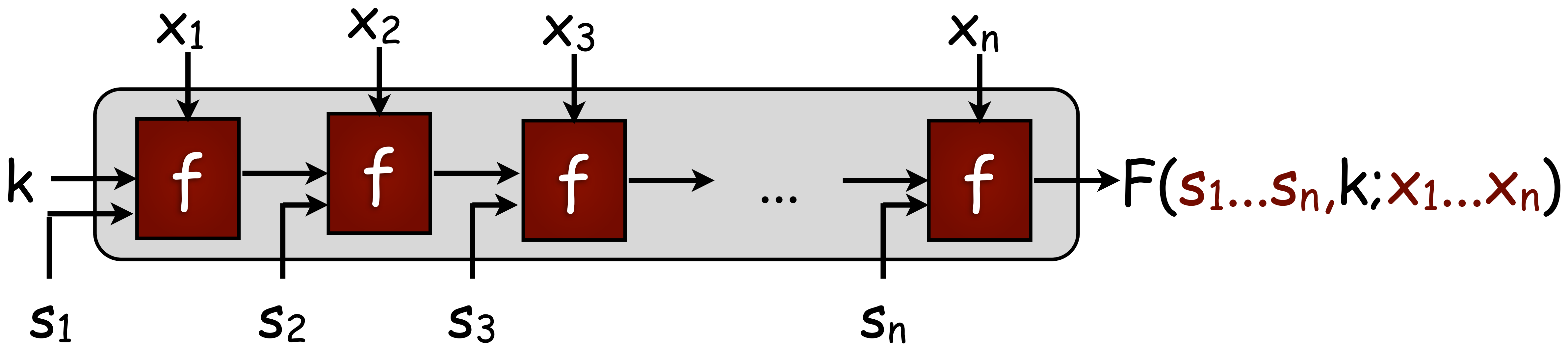

Key from $S^n \times K$, inputs from X^n

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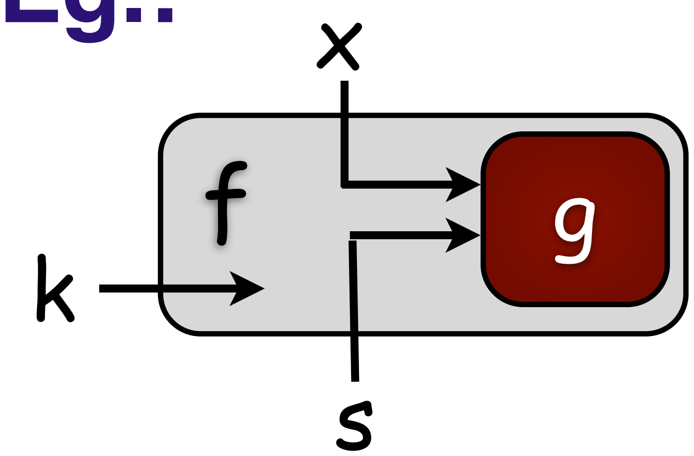

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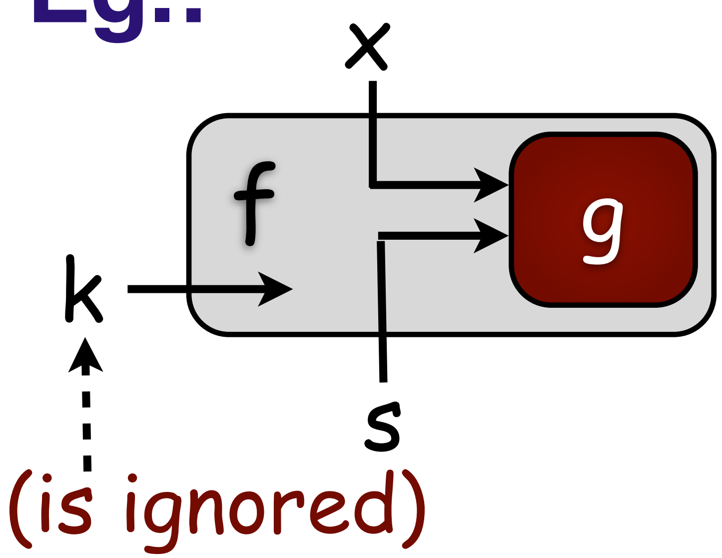

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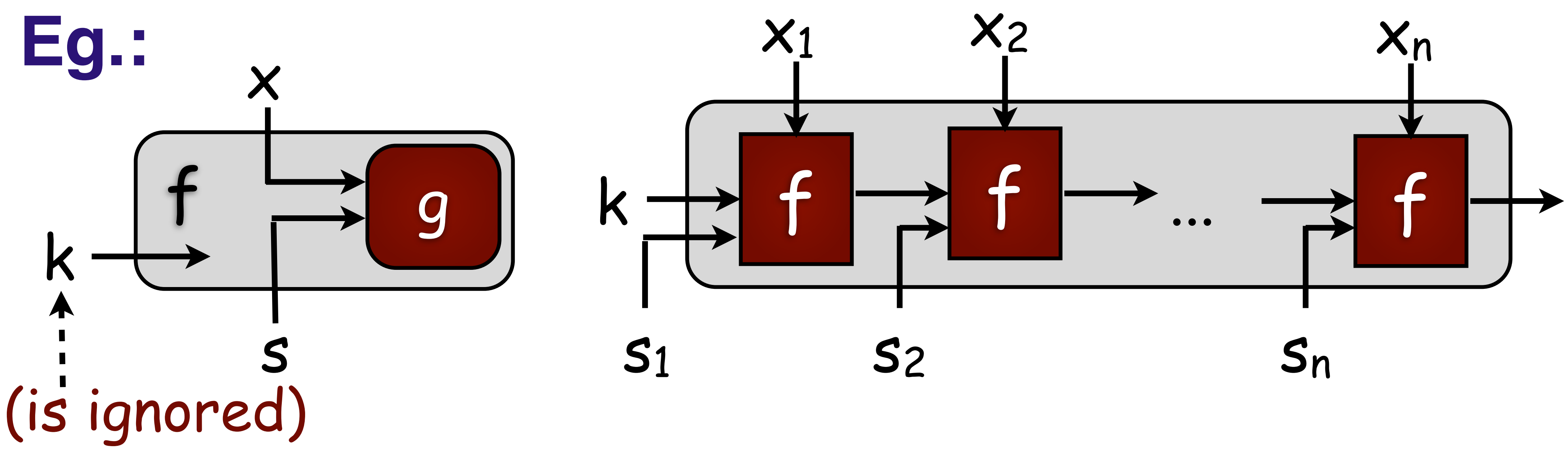

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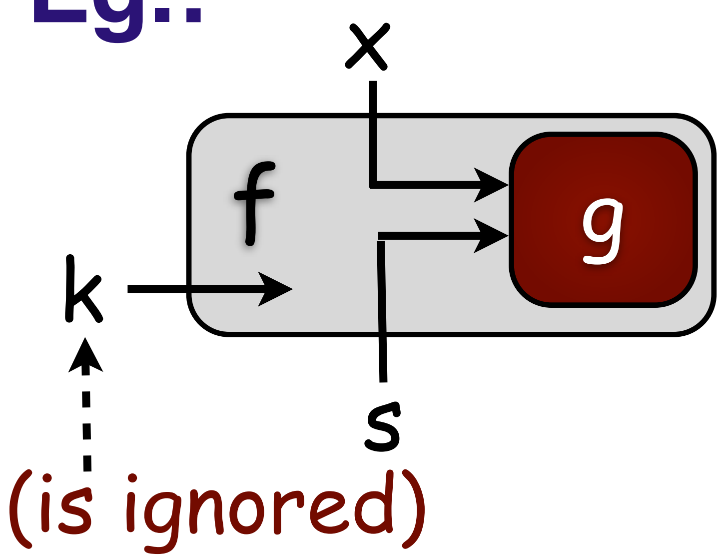

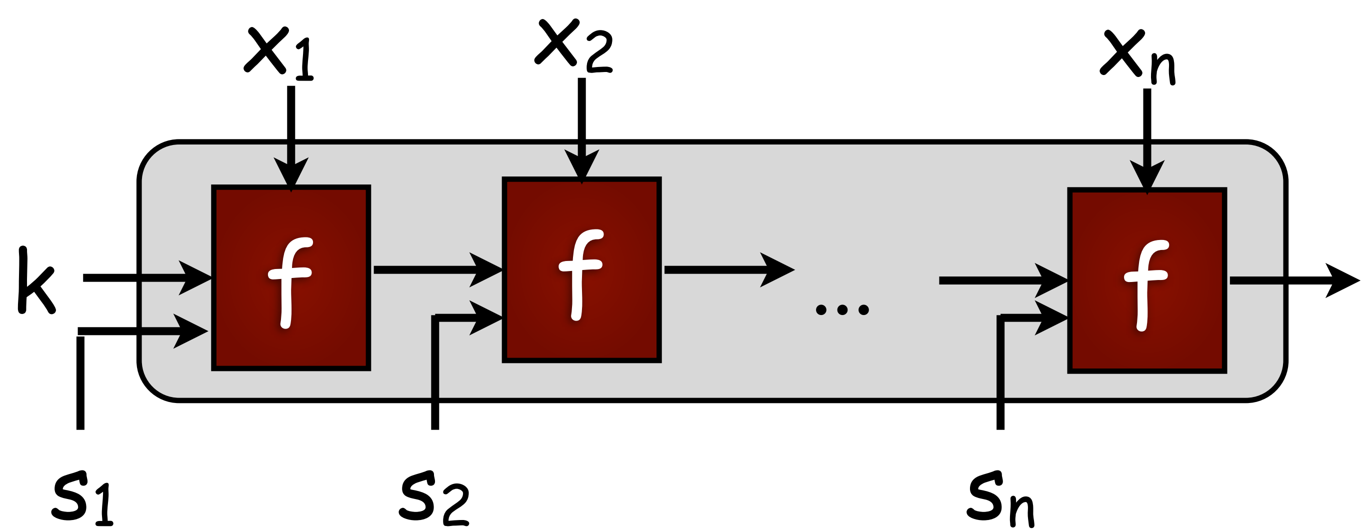

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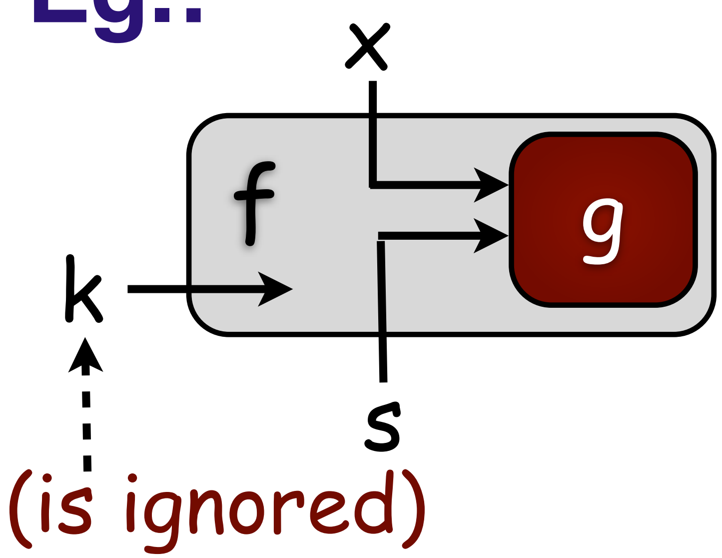

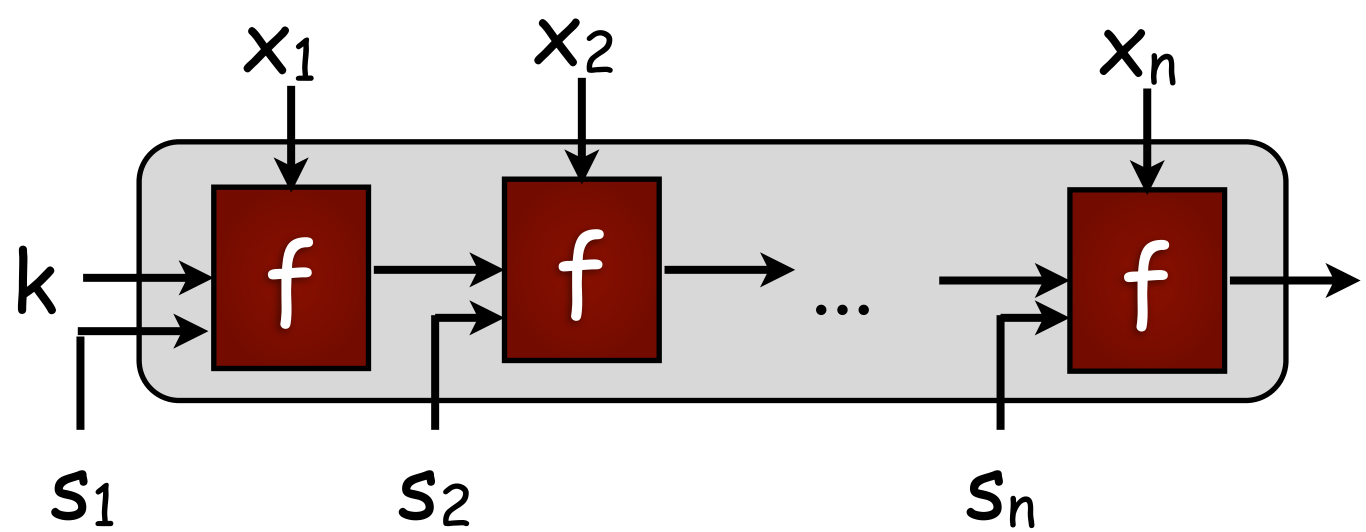

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Challenger

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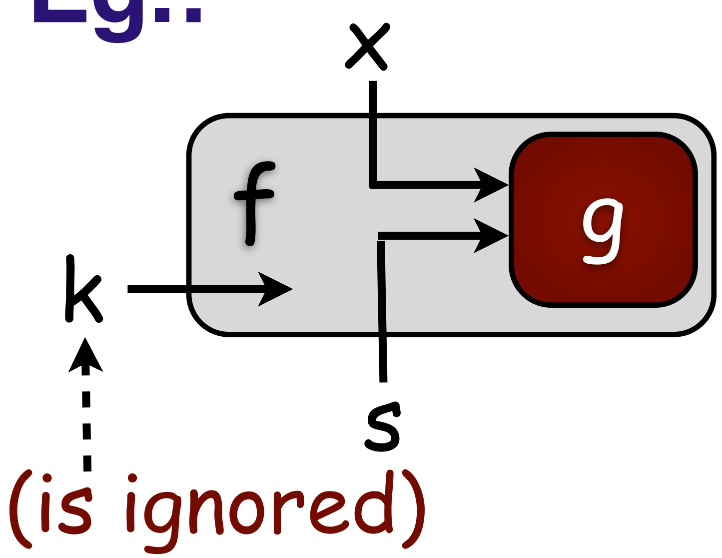

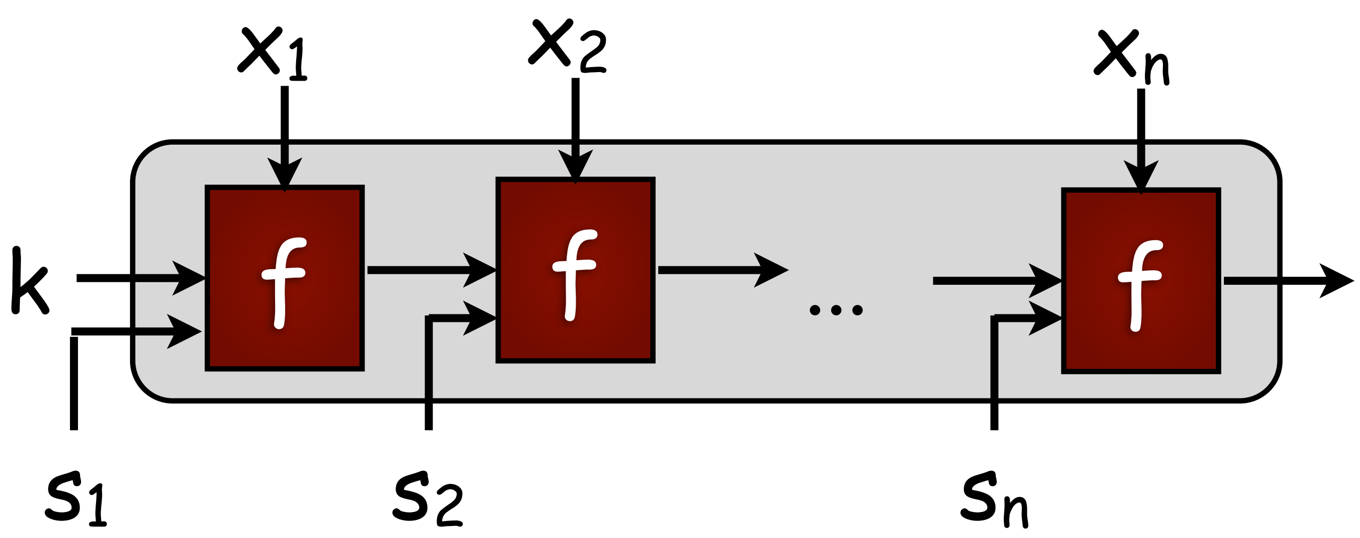

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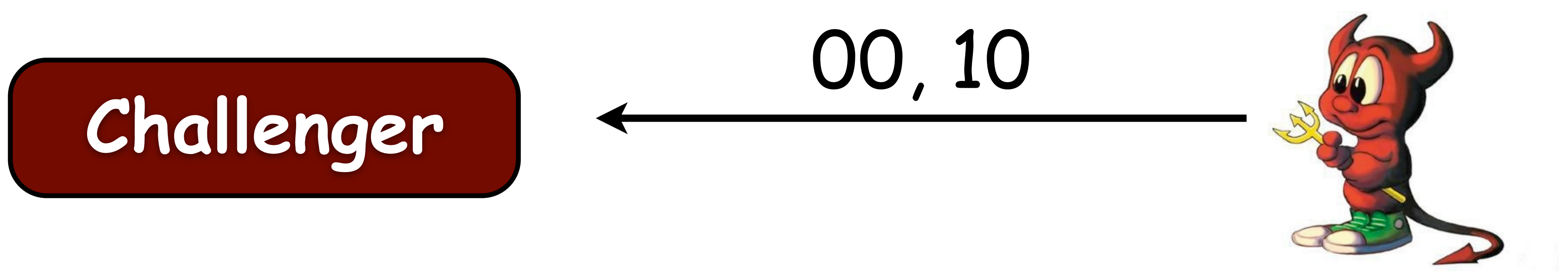

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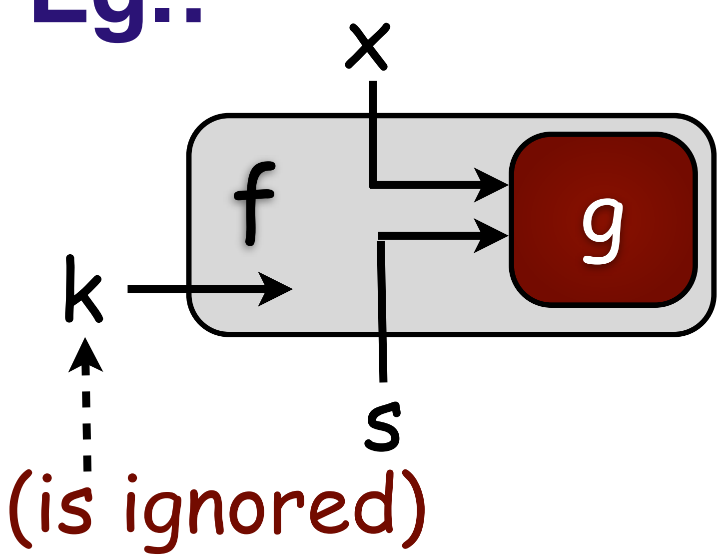

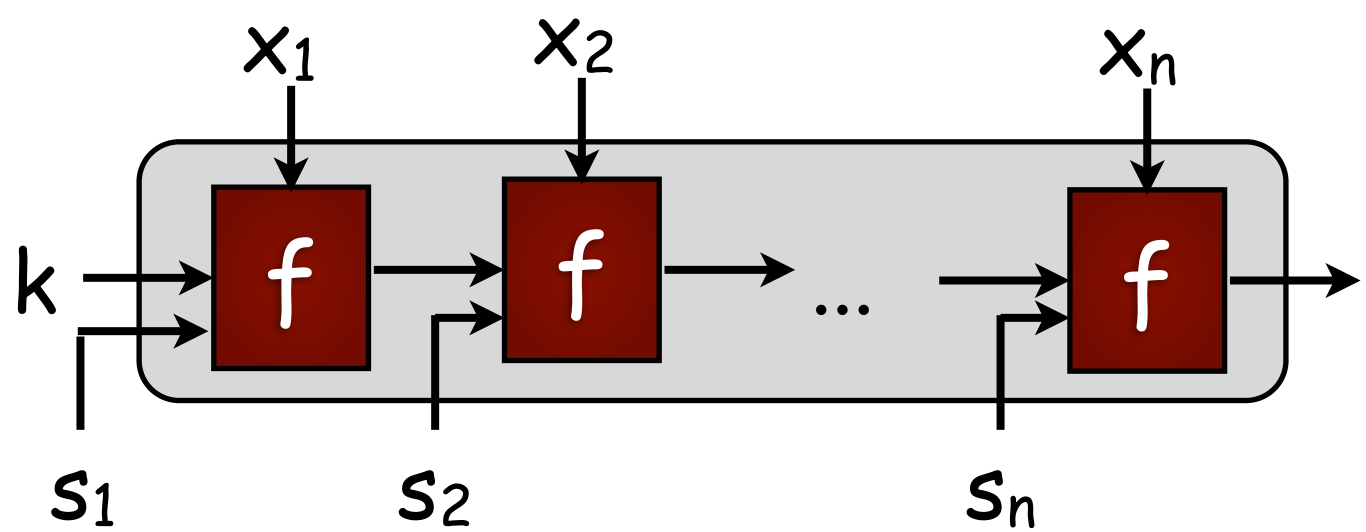

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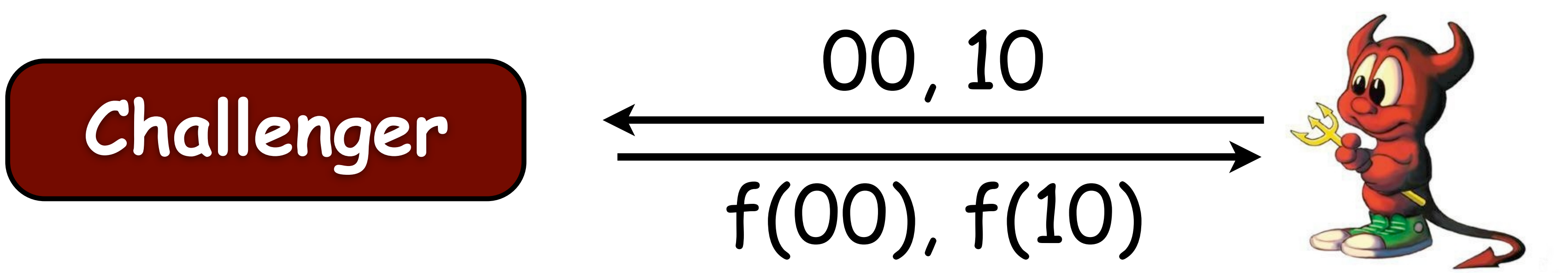

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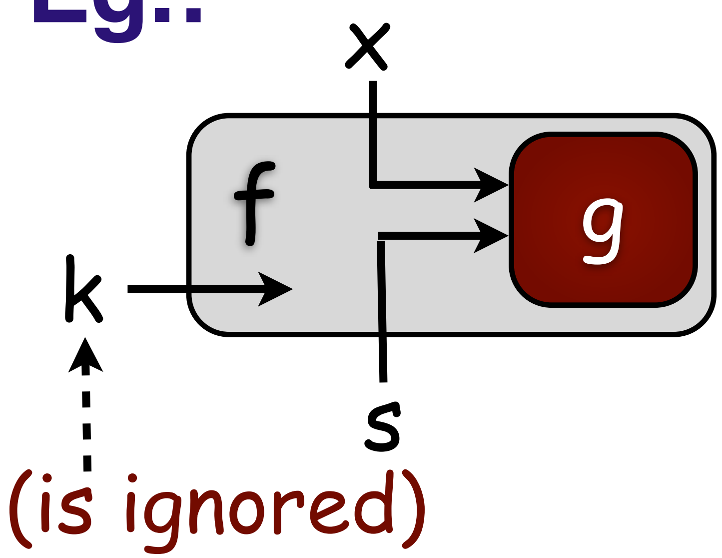

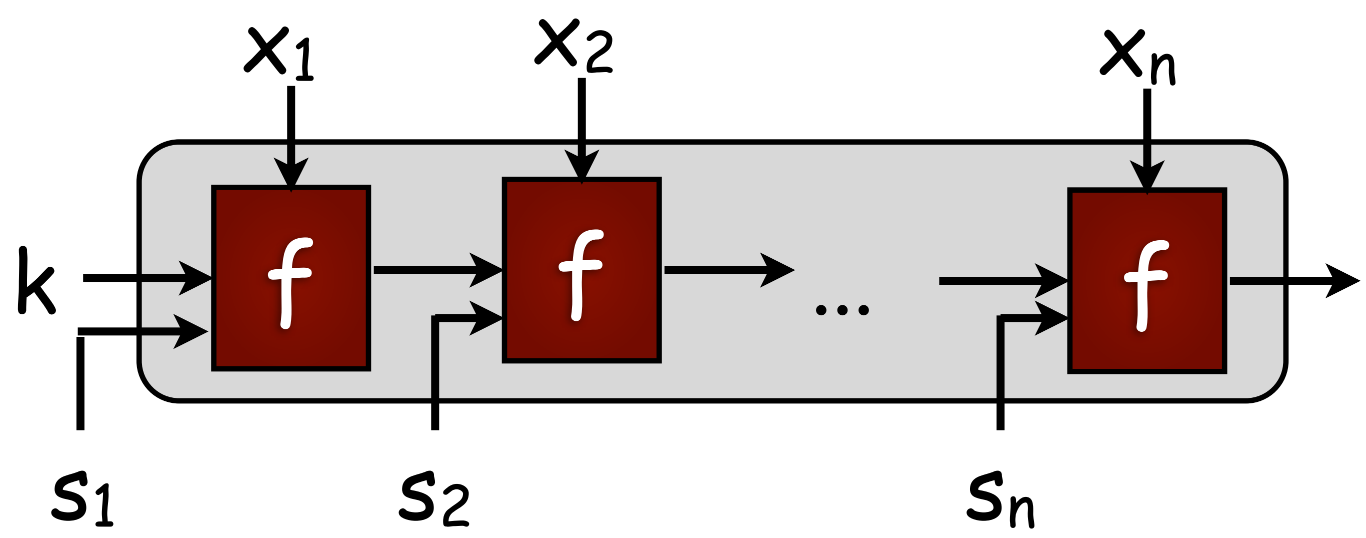

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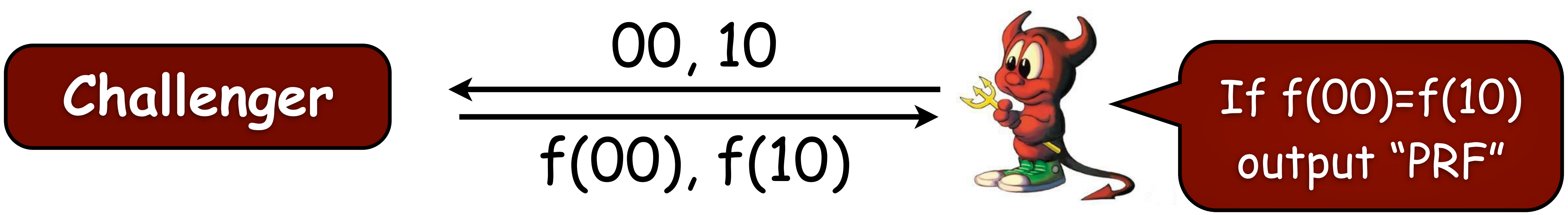

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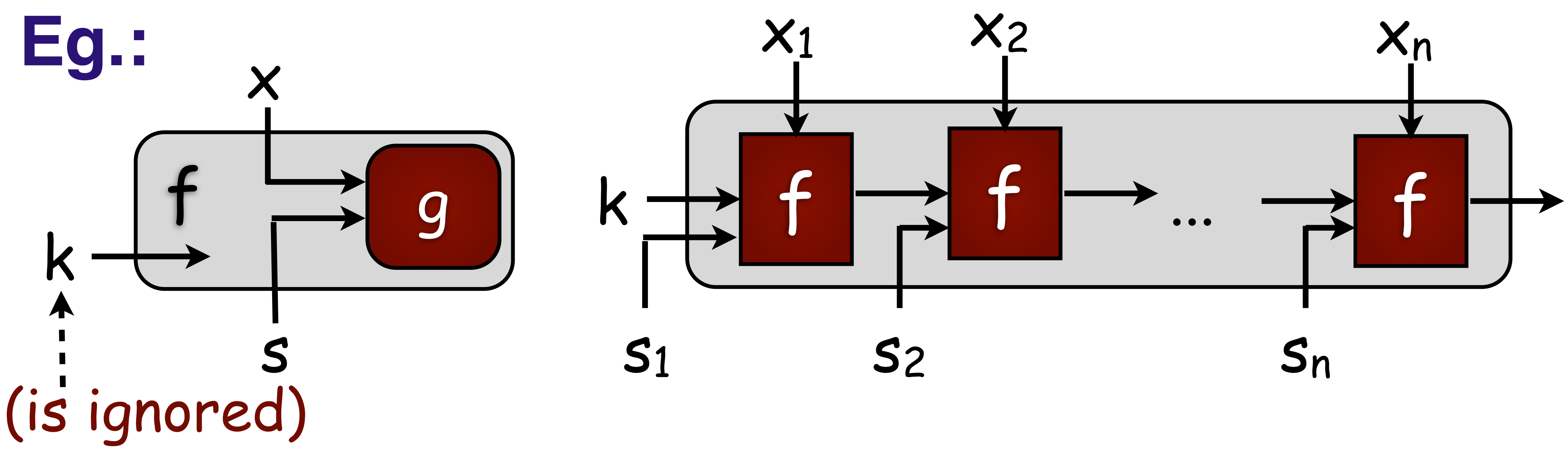

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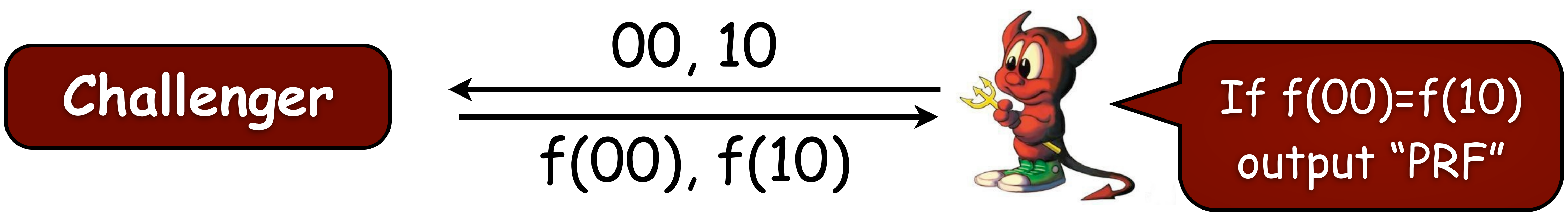

f(00)=f(10) for random f with very low probability

Therefore, F is not a secure PRF!

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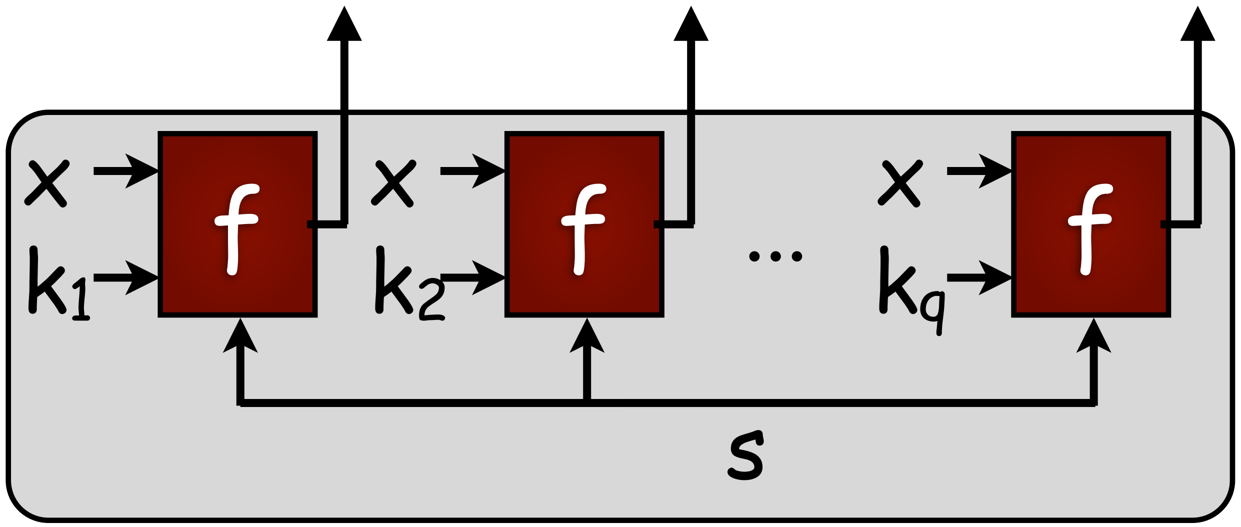

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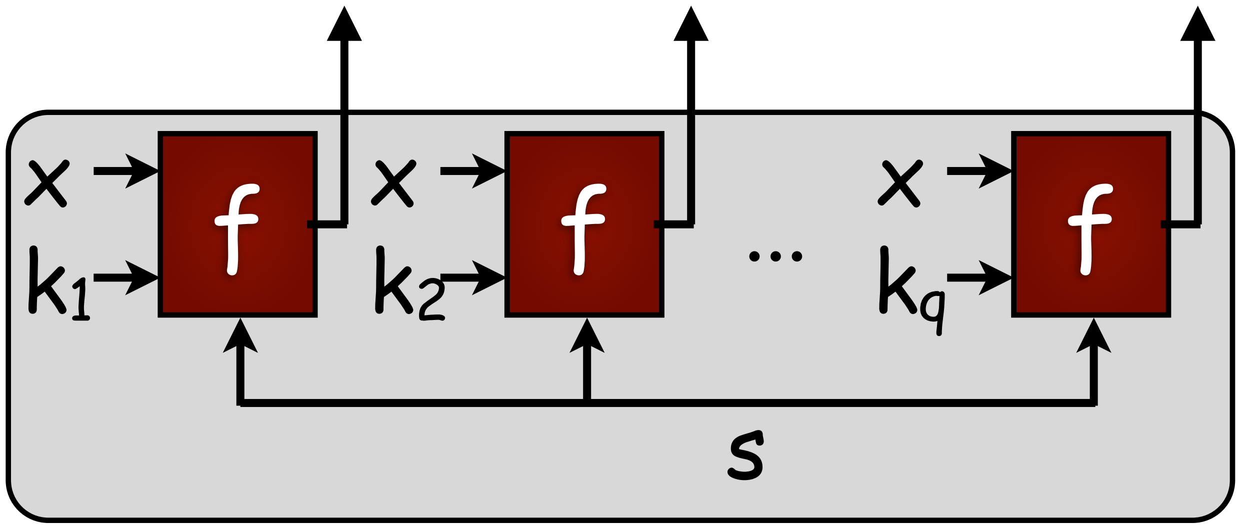
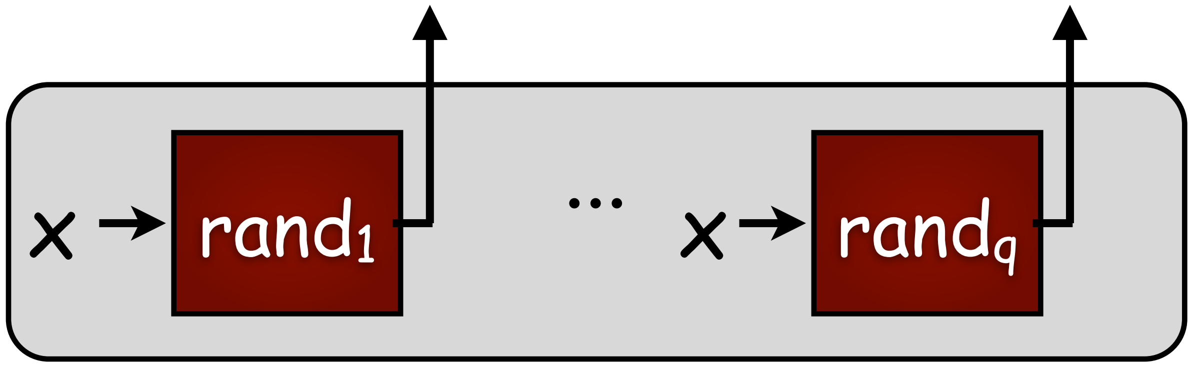


These functions look like q random functions



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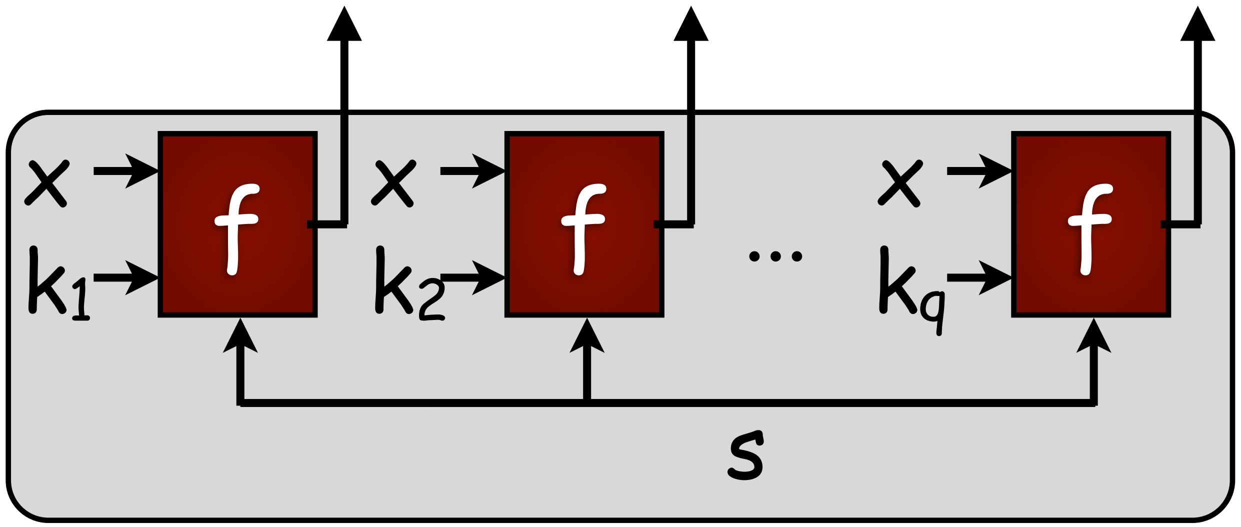

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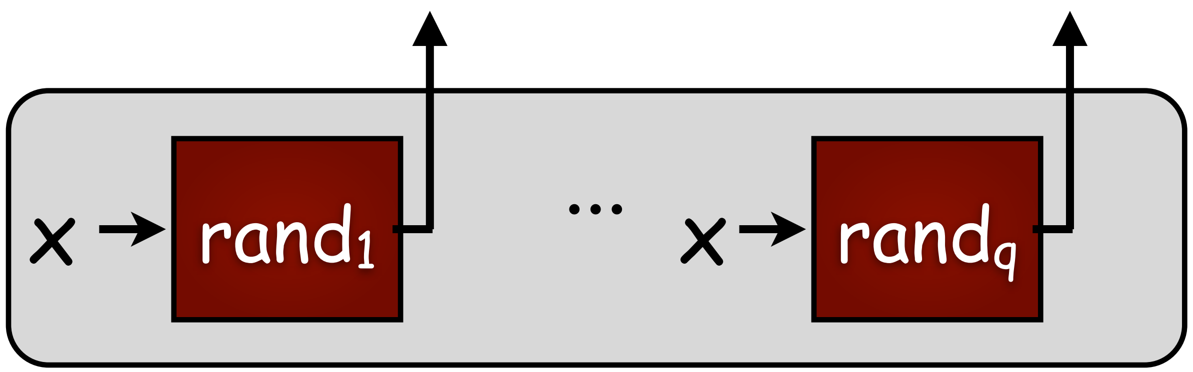

In other words:

"Simultaneously Secure"

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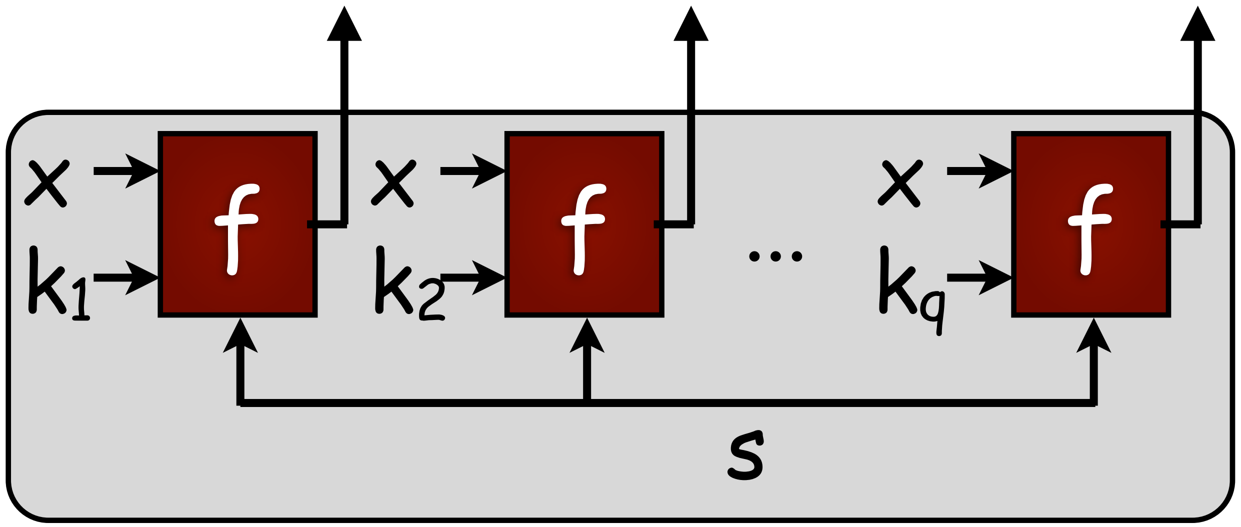

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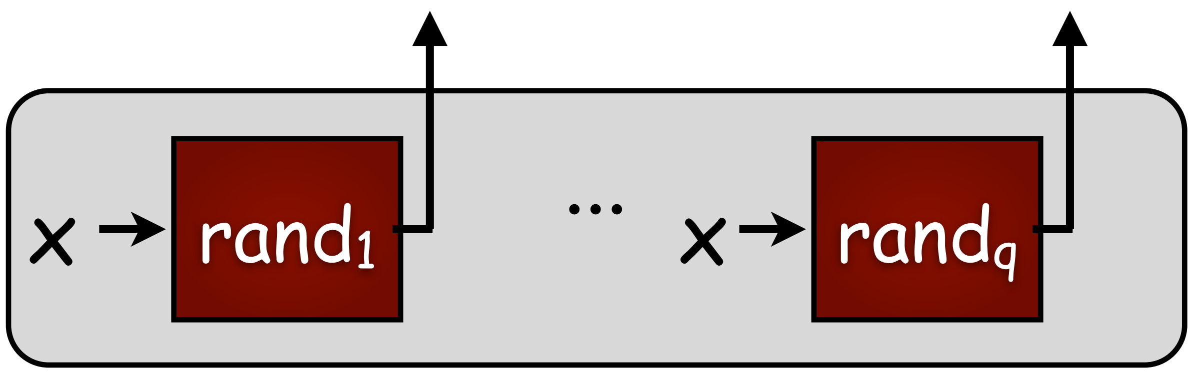

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Theorem

f is a q-parallel secure PRF $\Longrightarrow$ F is a secure PRF

Proof Outline

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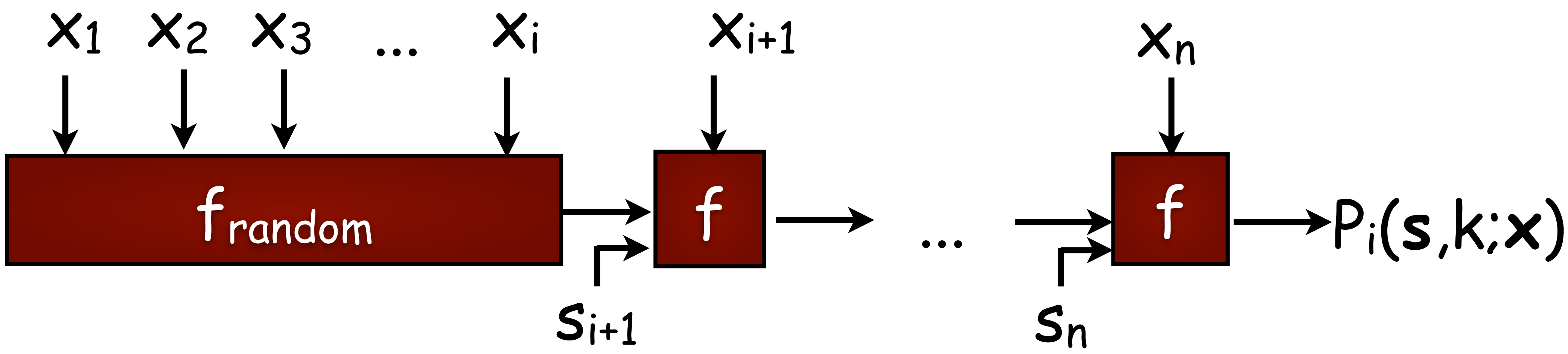

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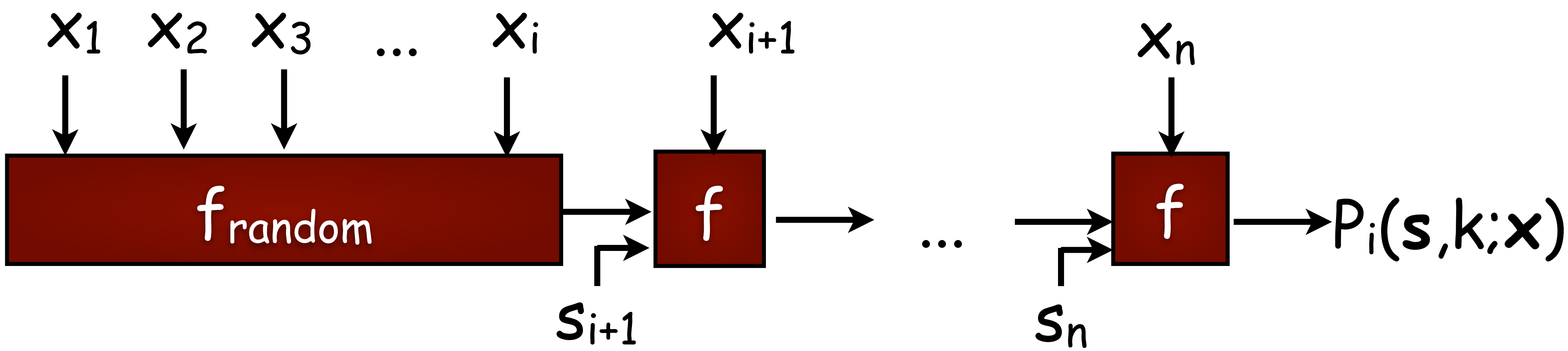

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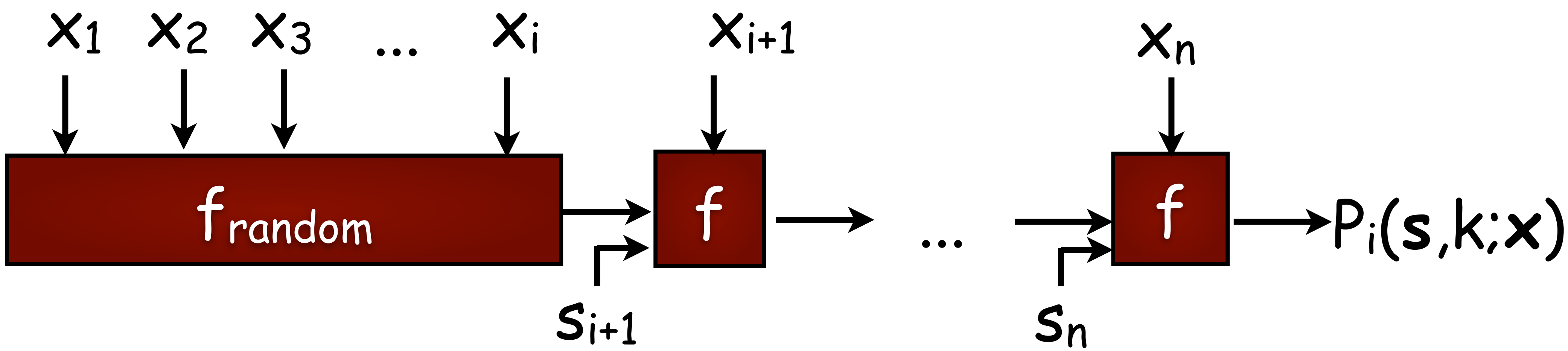

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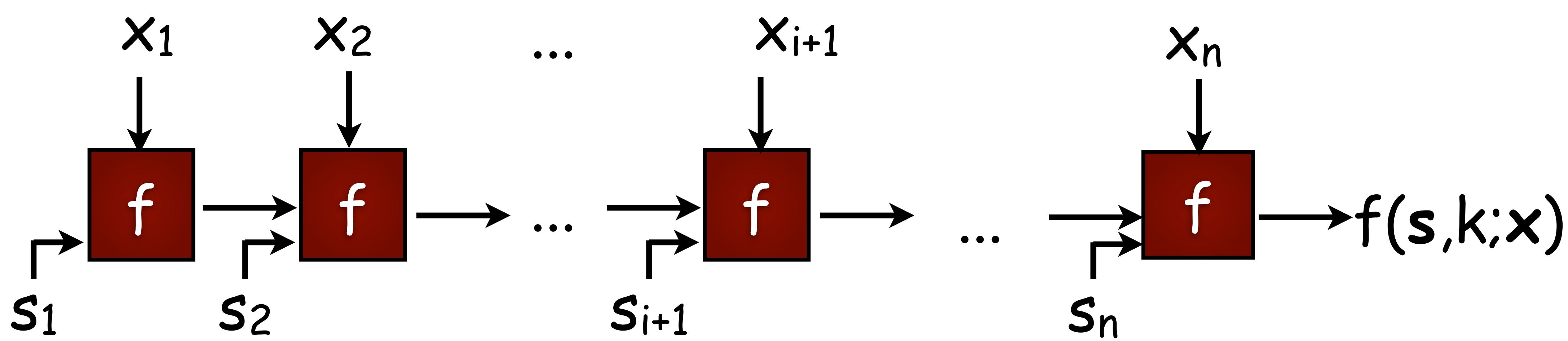

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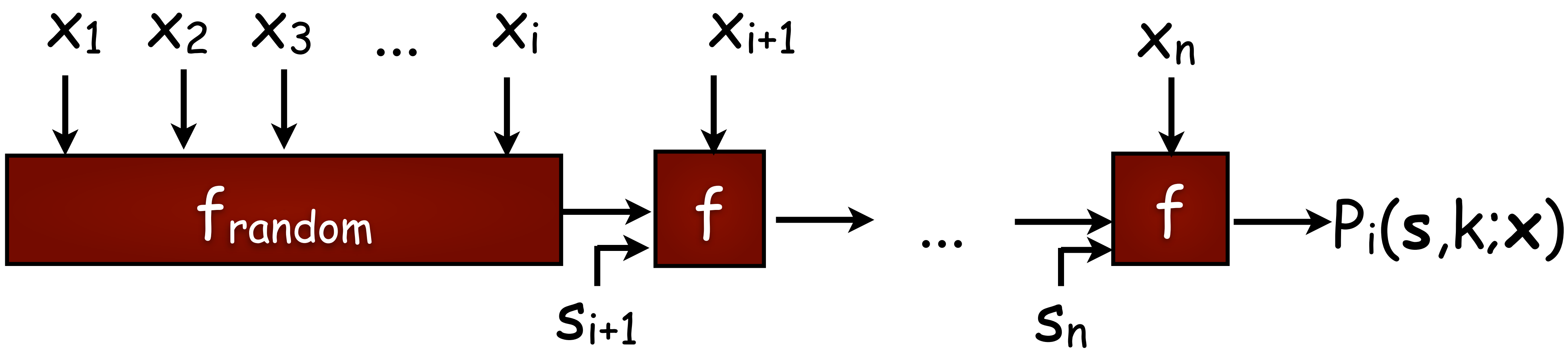

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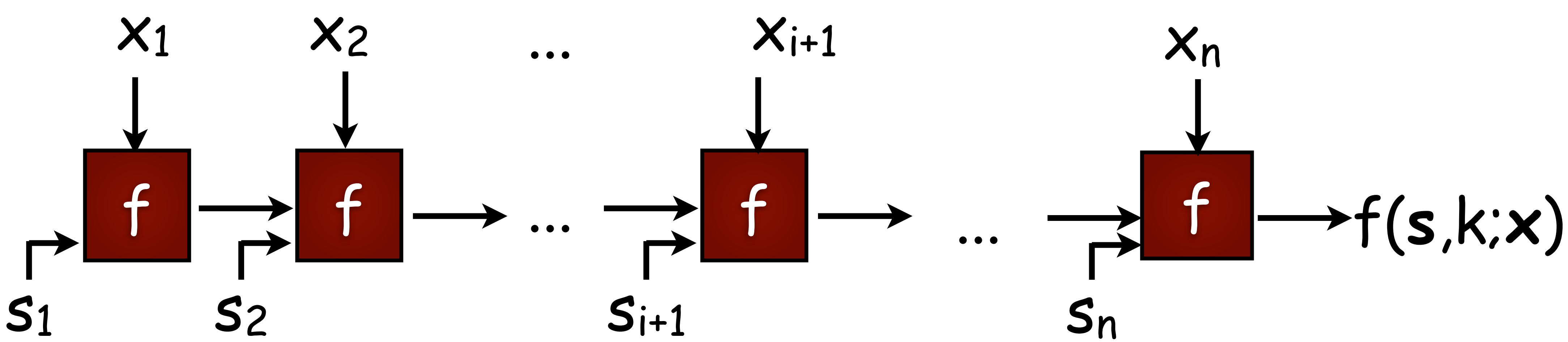

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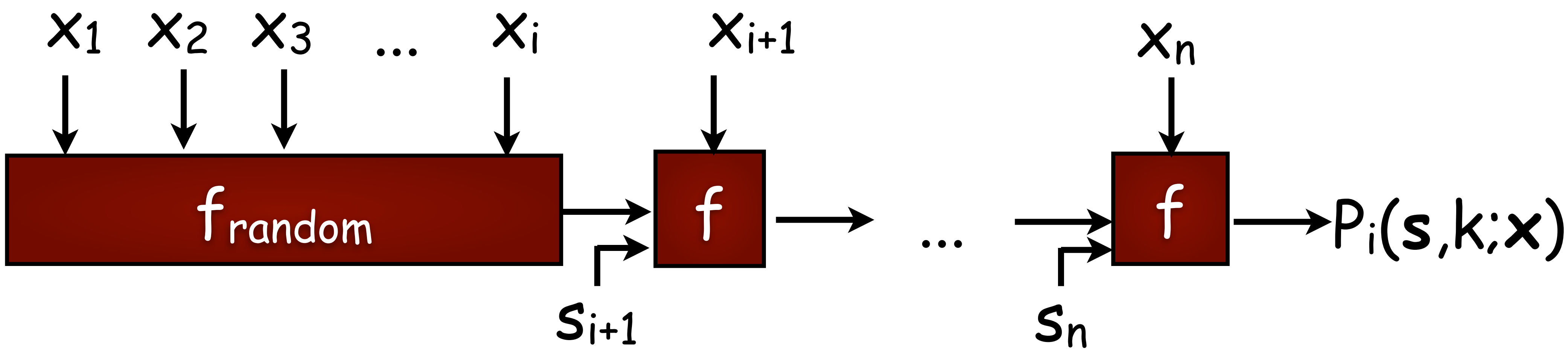

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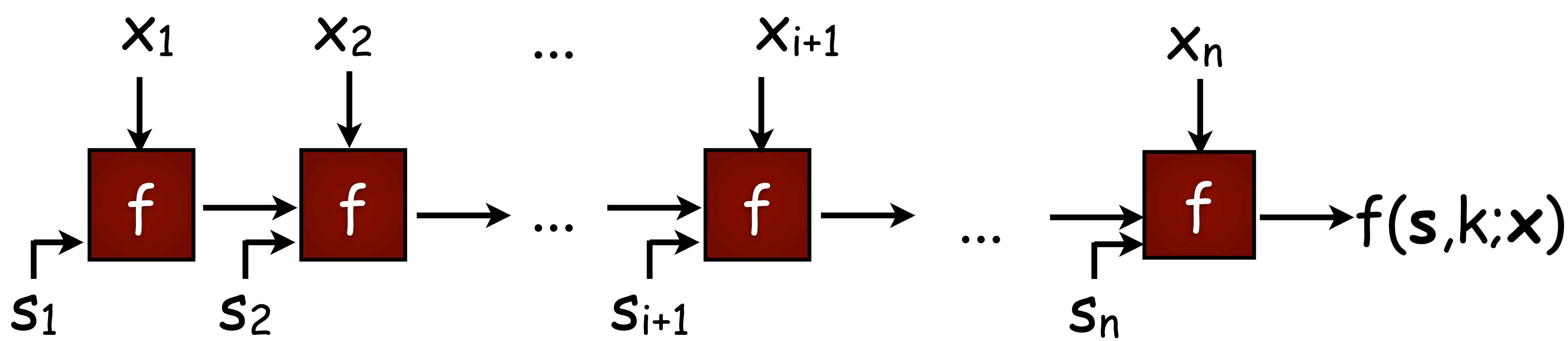

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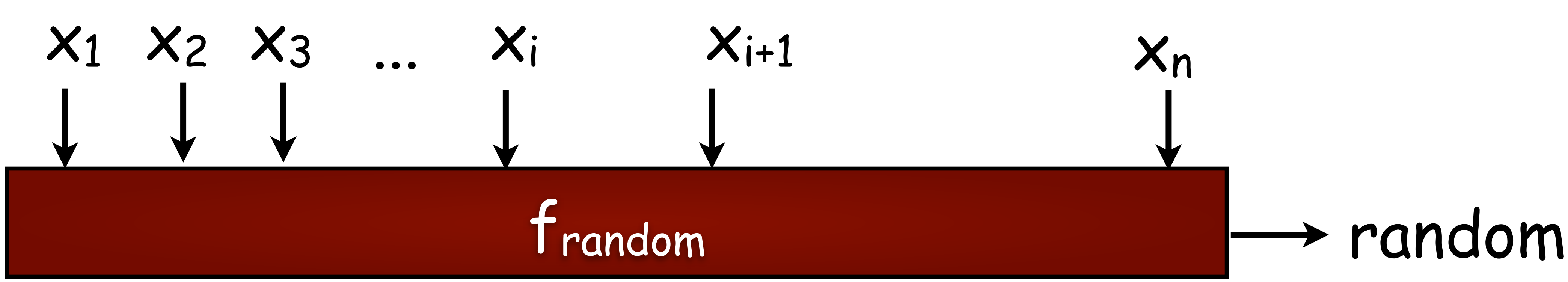
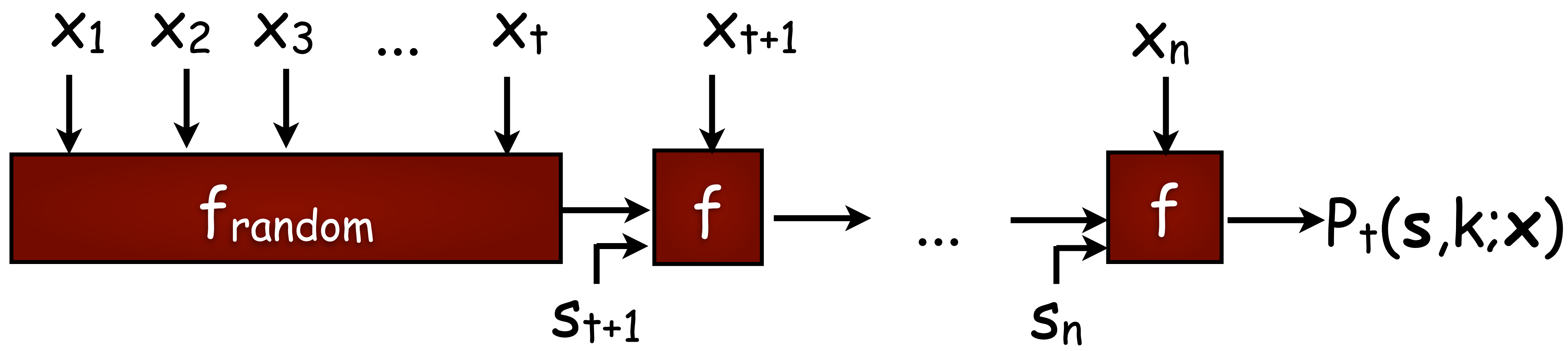


Proof Outline



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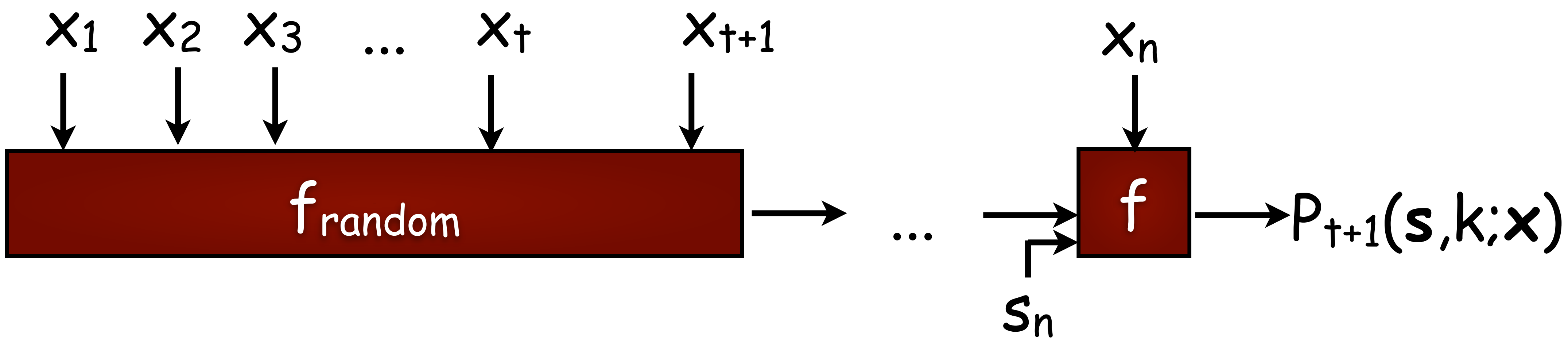

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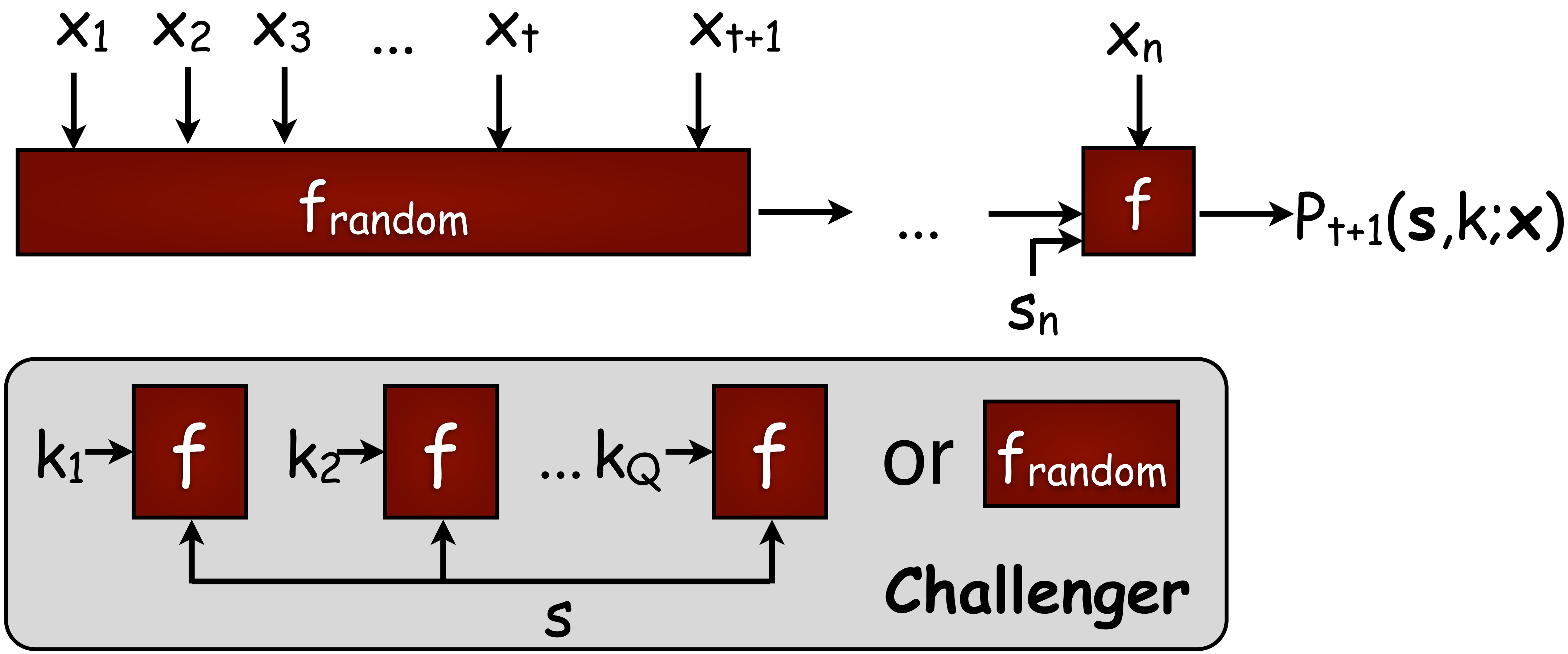

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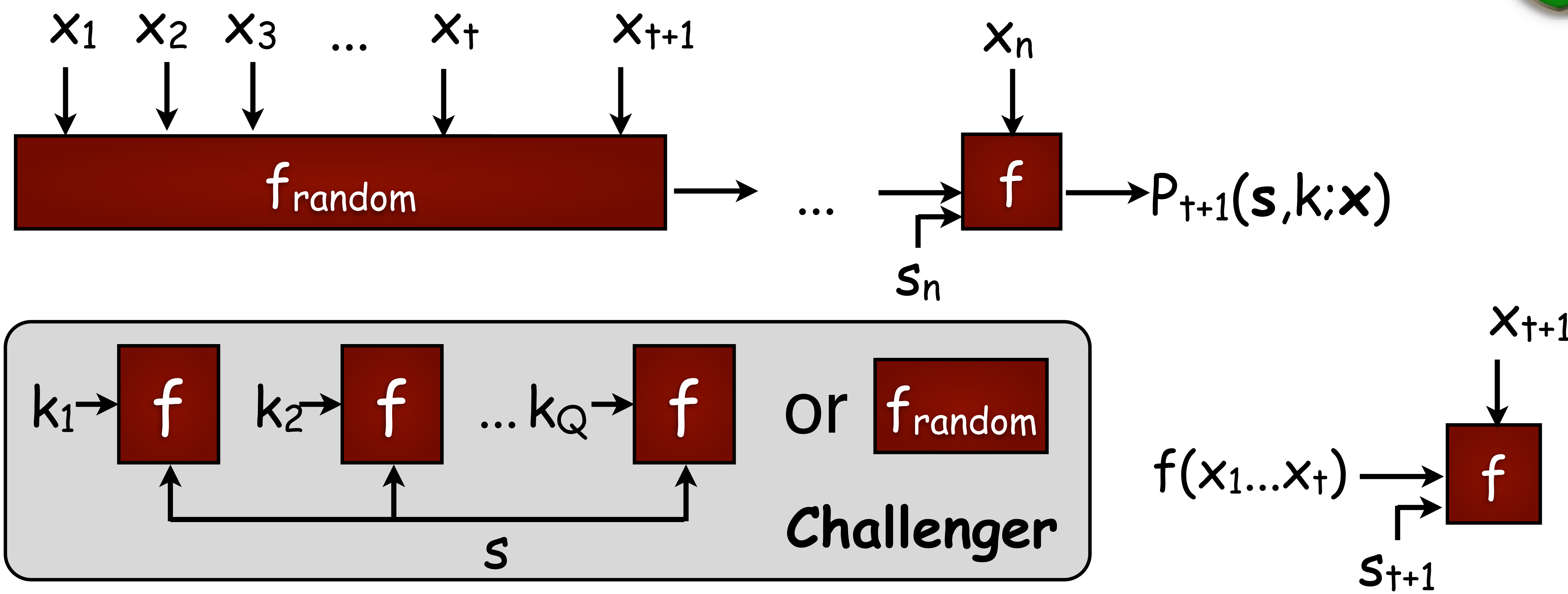

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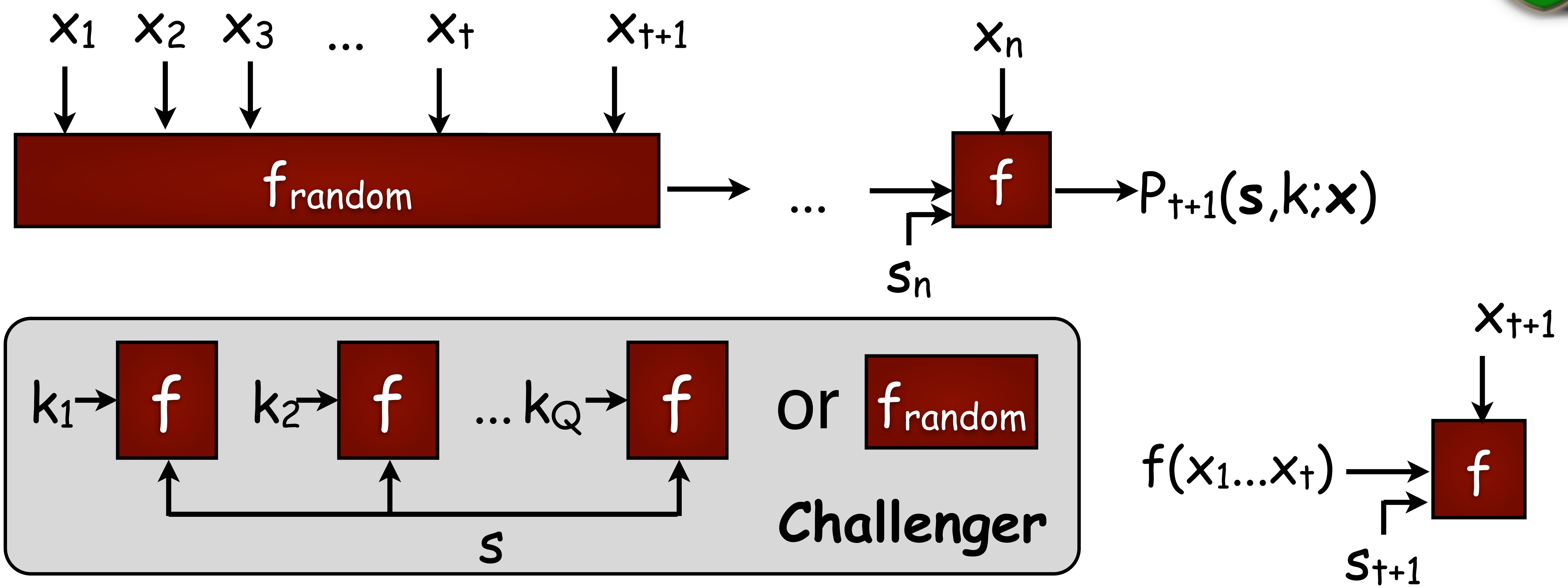

s_{t+1} is set to s

Depending on $x_1 \ldots x_t$ we choose the value of $f(x_1 \ldots x_t)$ to be some key k_j – maintained in an associative table

Easy to see: We simulate either P_t or P_{t+1} depending upon Challenger

Why Augmented Cascade?

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- Generic tool to build efficient algebraic PRFs

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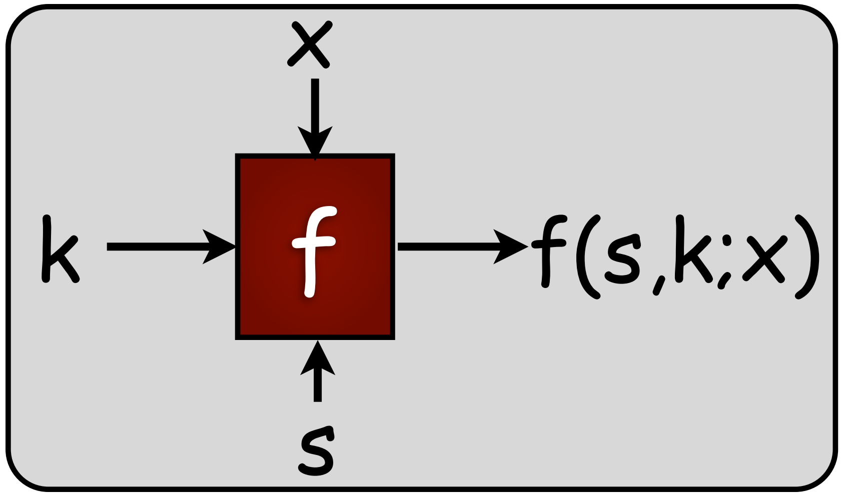

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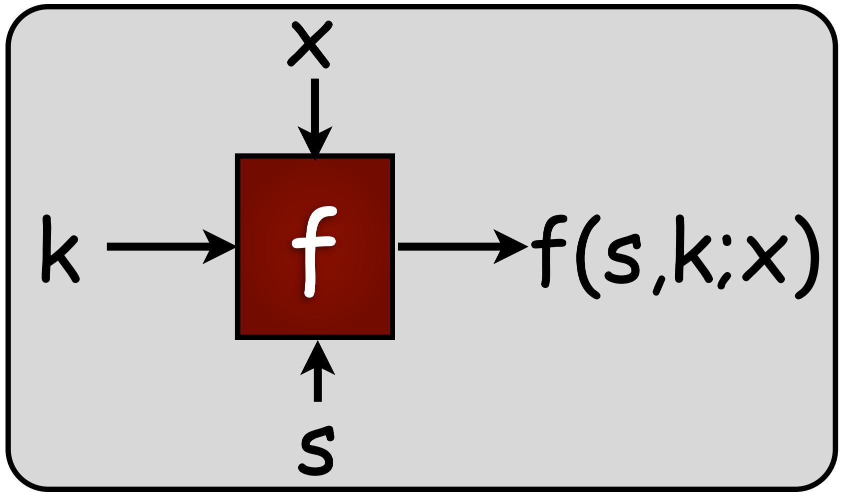

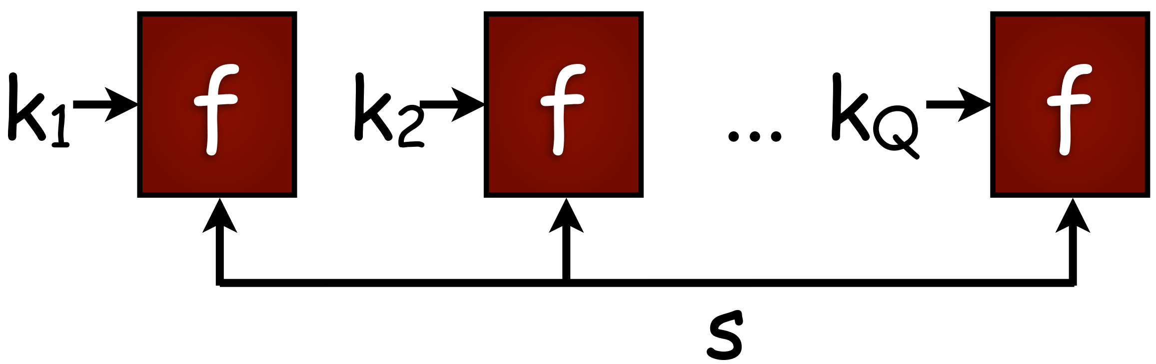

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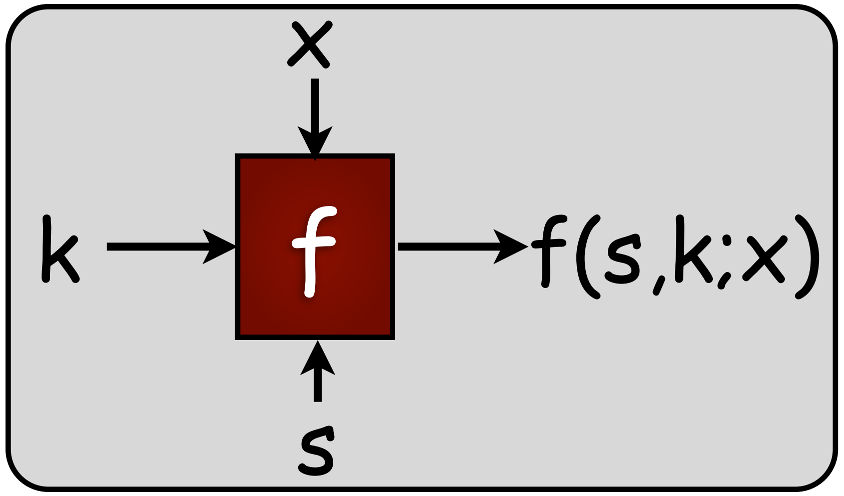

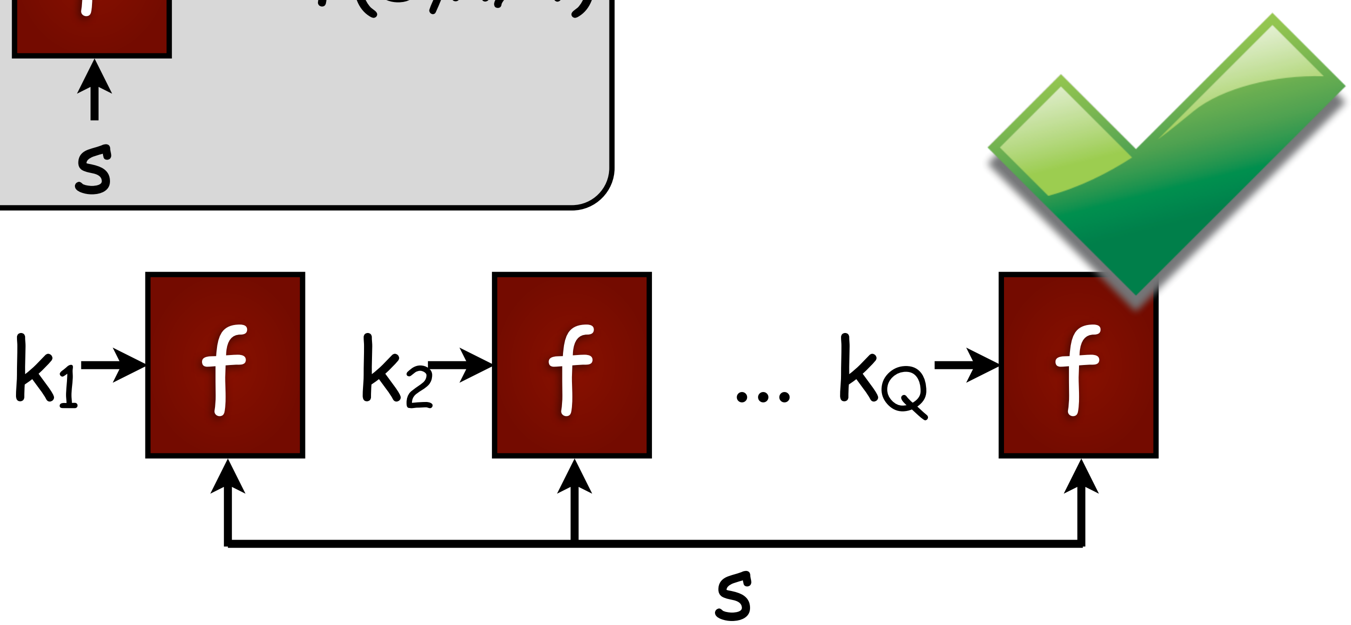

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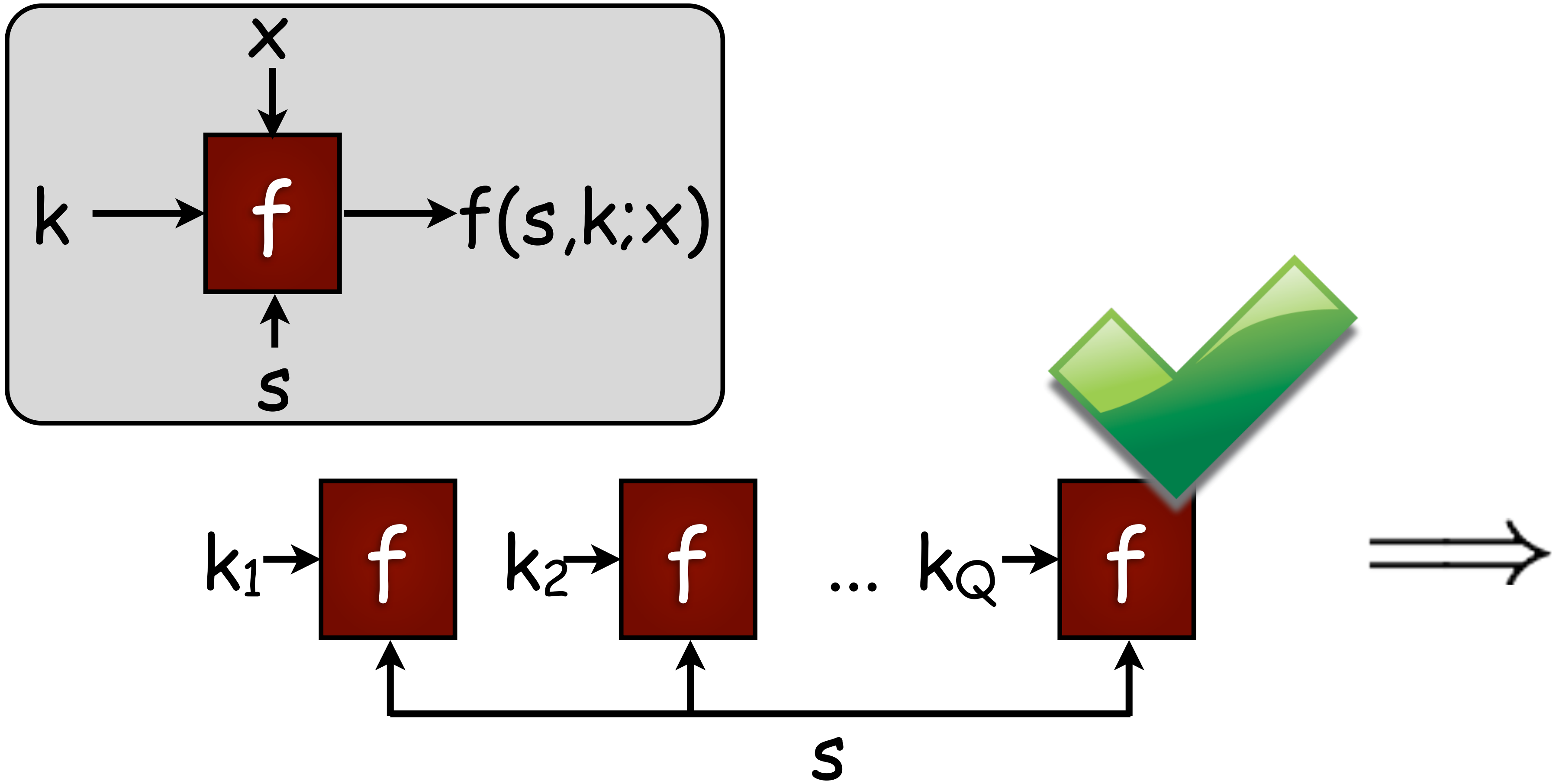

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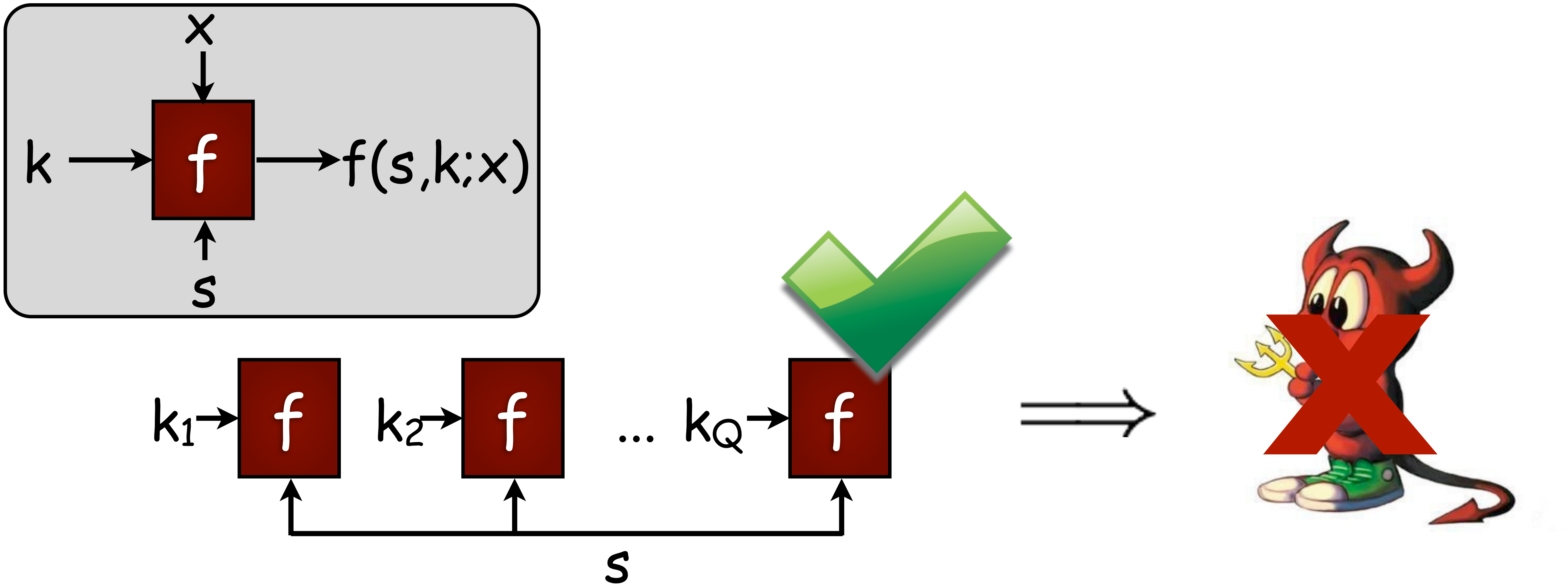

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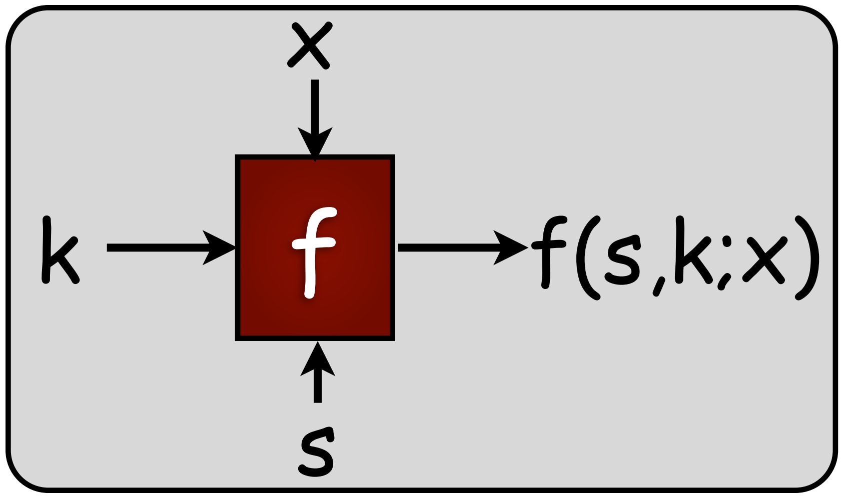

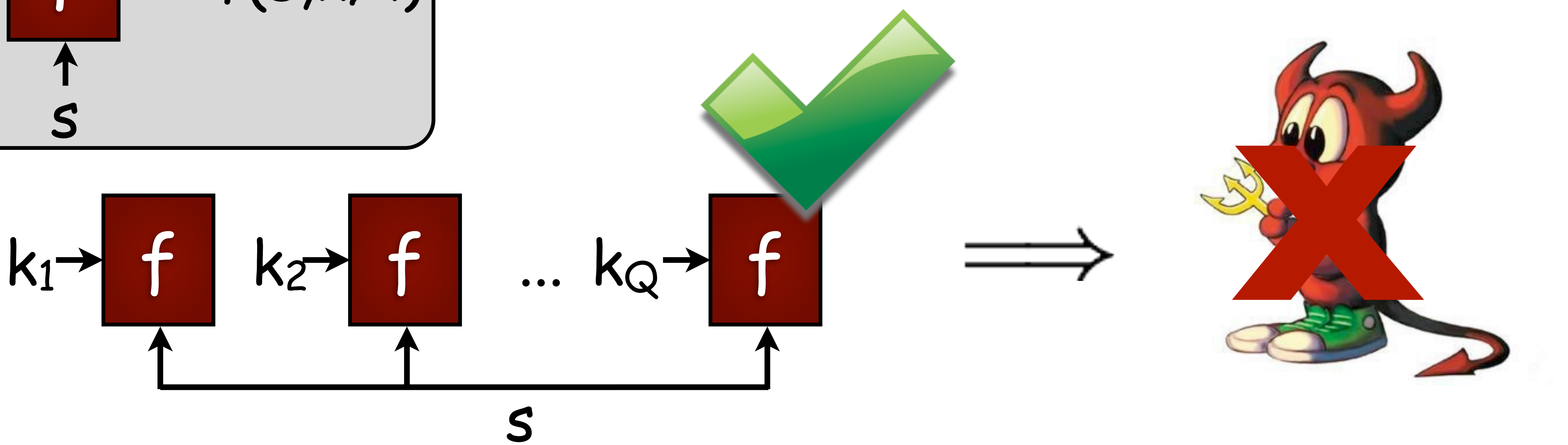

- Simple proofs for existing algebraic PRFs. We show q-parallel security of:
  Naor-Reingold [FOCS '97] & Lewko-Waters [CCS '09]

Naor-Reingold [FOCS '97]

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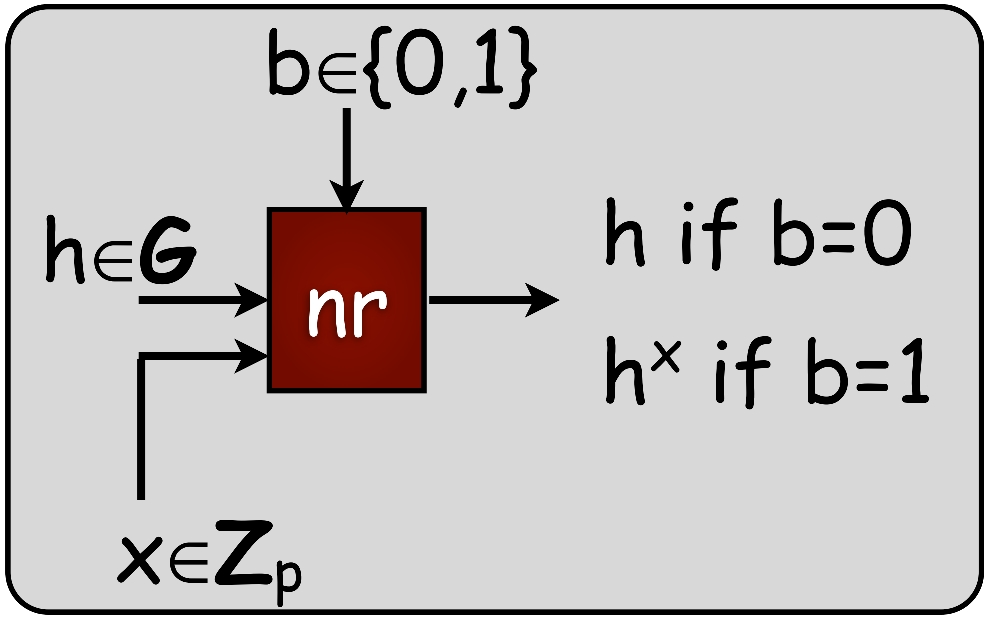

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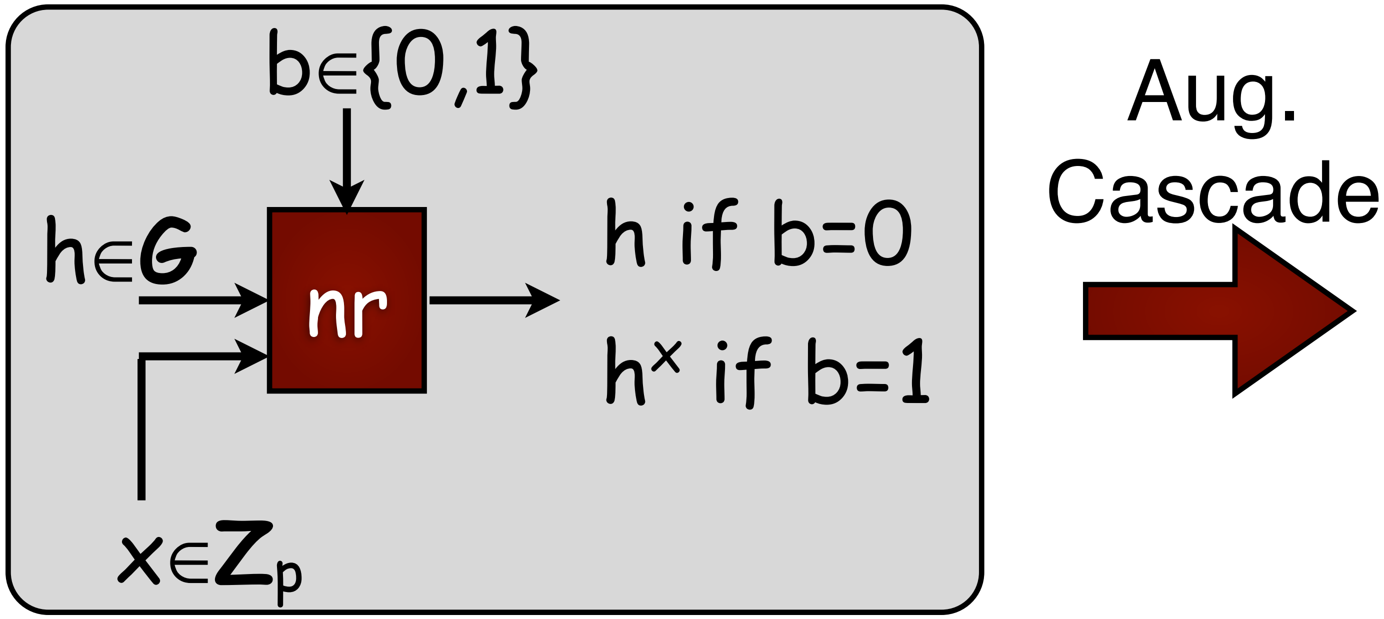

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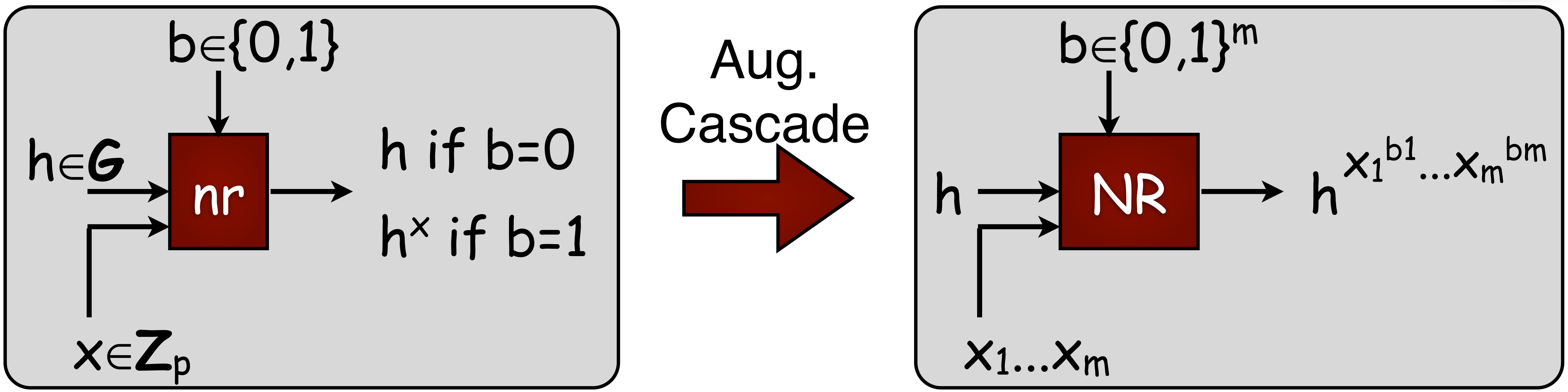

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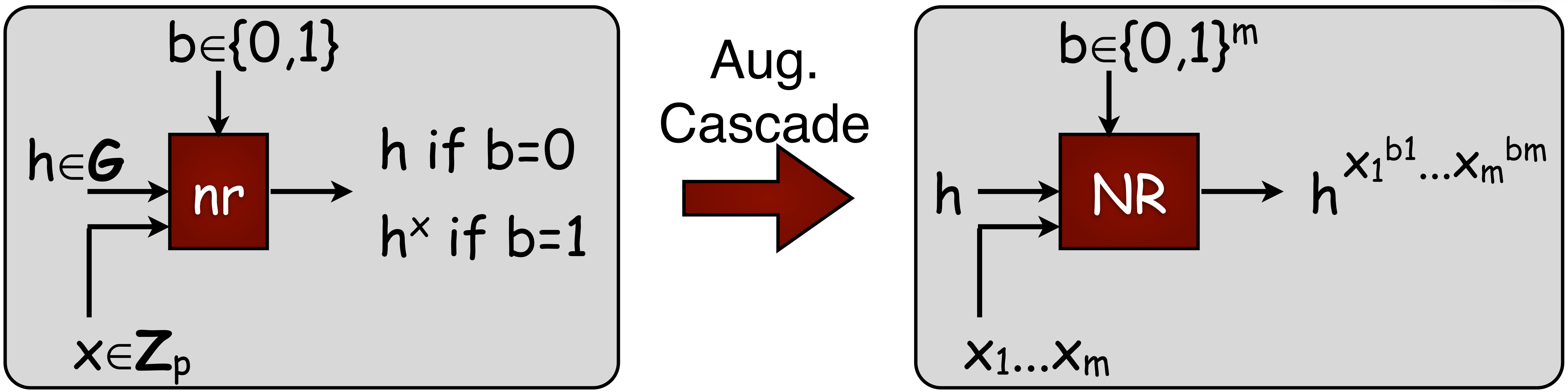

Theorem: $\boxed{nr}$ is q-parallel secure under the DDH assumption

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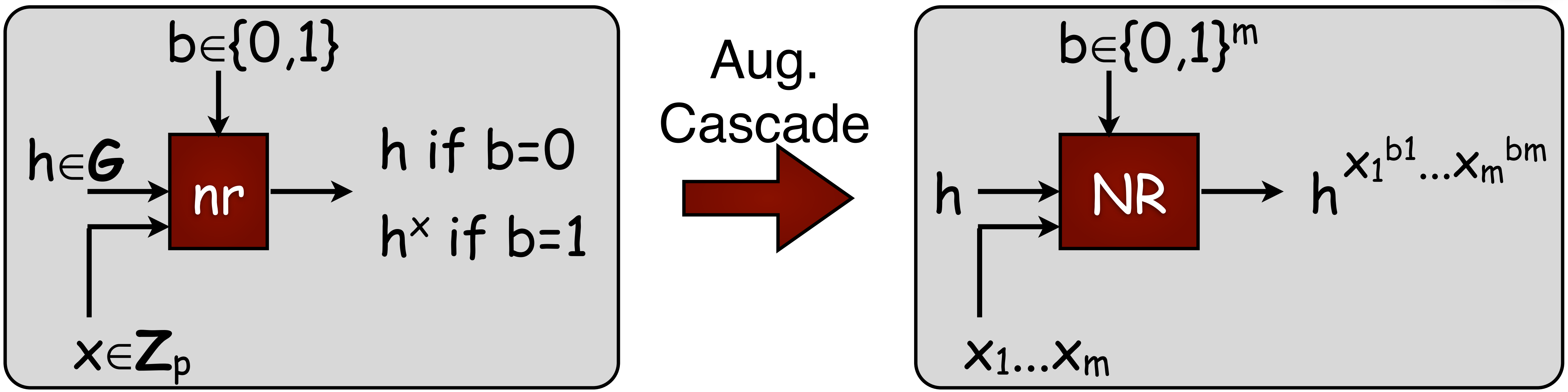

Theorem: nr is q-parallel secure under the DDH assumption

Group **G** of prime order p with generator *g*.
g^{ab} looks random in G**,**given g^a,g^b for random *a*,*b*,

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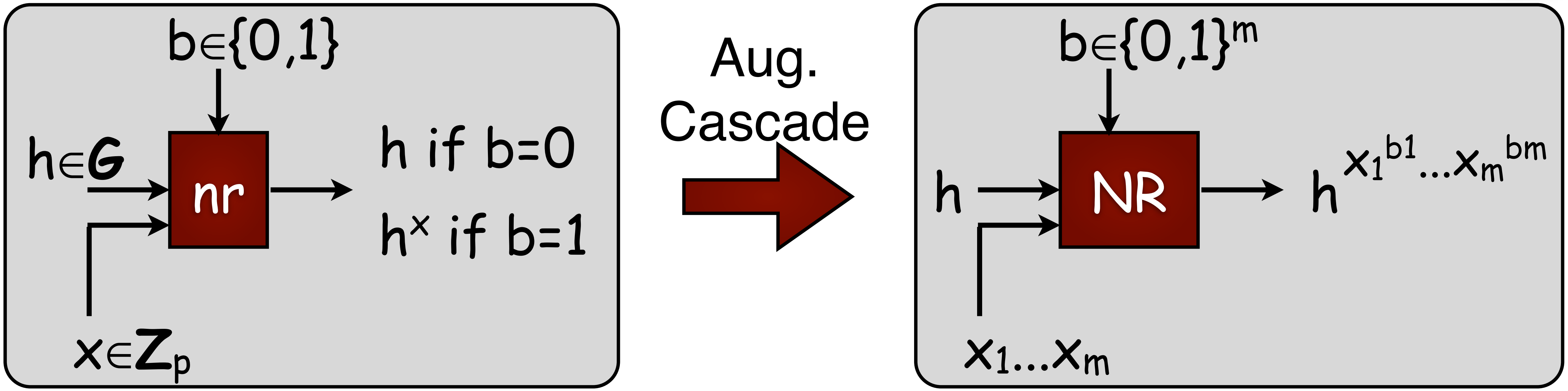

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Corollary: $\boxed{NR}$ is secure PRF under the DDH assumption

Lewko-Waters [CCS '09]

- Details in the paper

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Theorem: lw is q-parallel secure under the k-linear assumption

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Corollary: LW is secure PRF under the k-linear assumption

New Algebraic PRF

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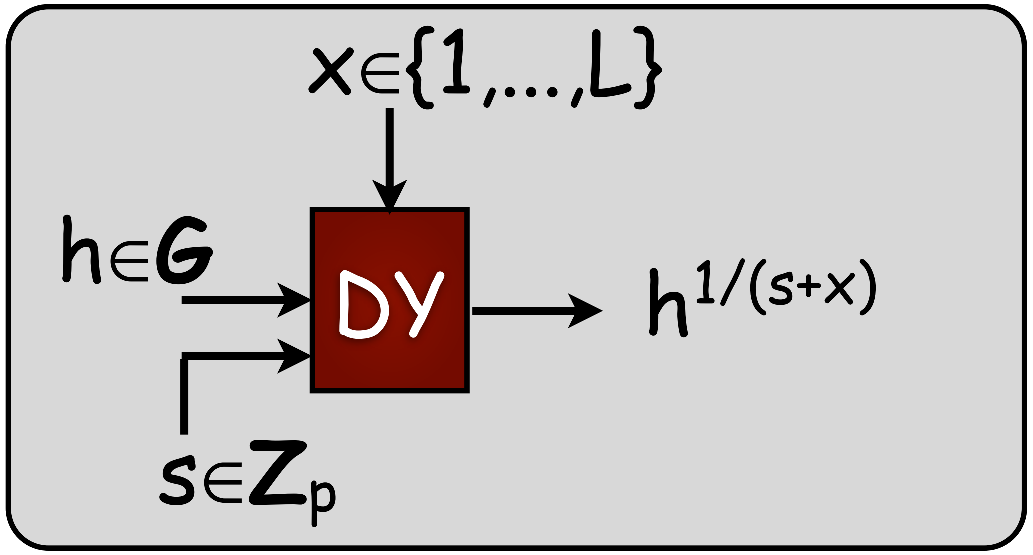
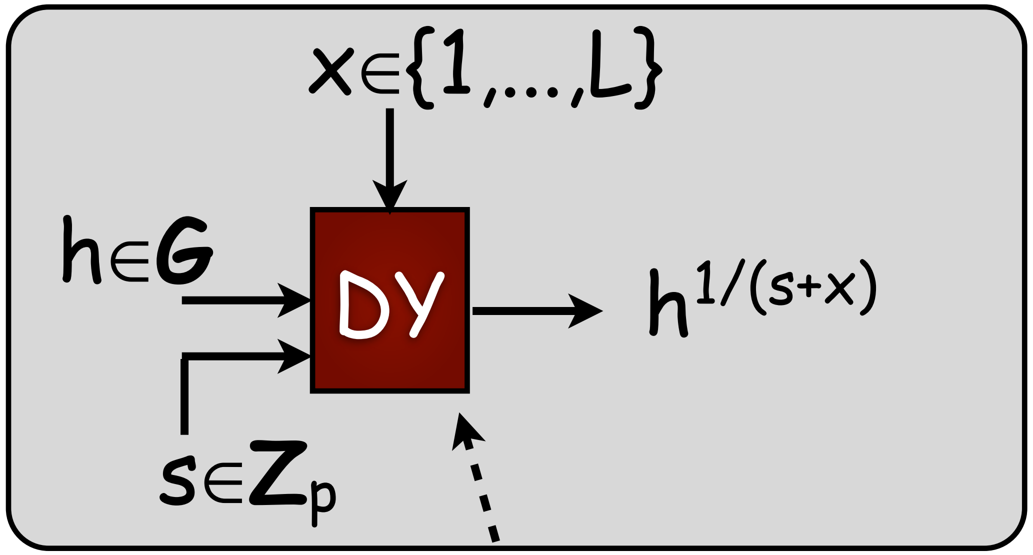
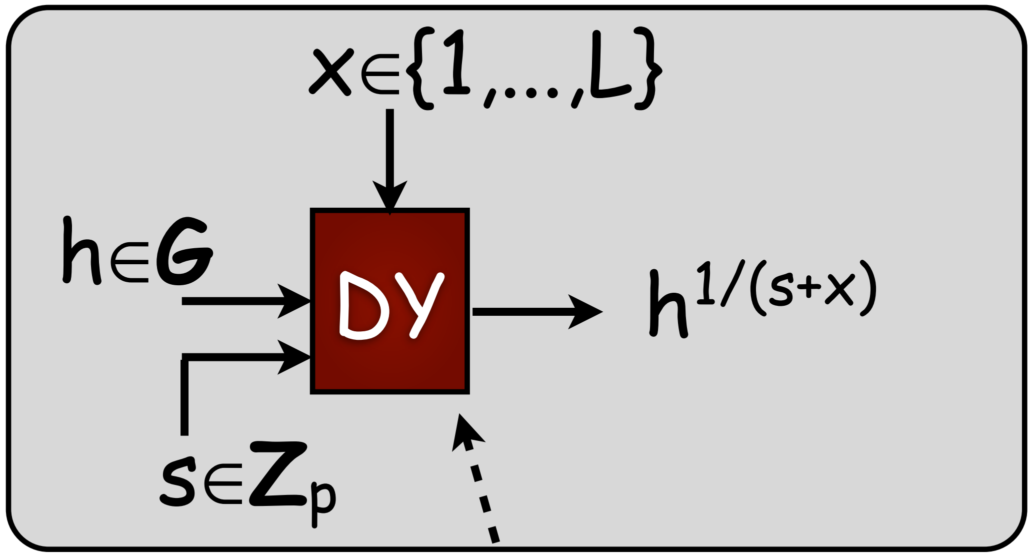


New Algebraic PRF



Dodis-Yampolskiy [PKC '05]

New Algebraic PRF



Aug.
Cascade

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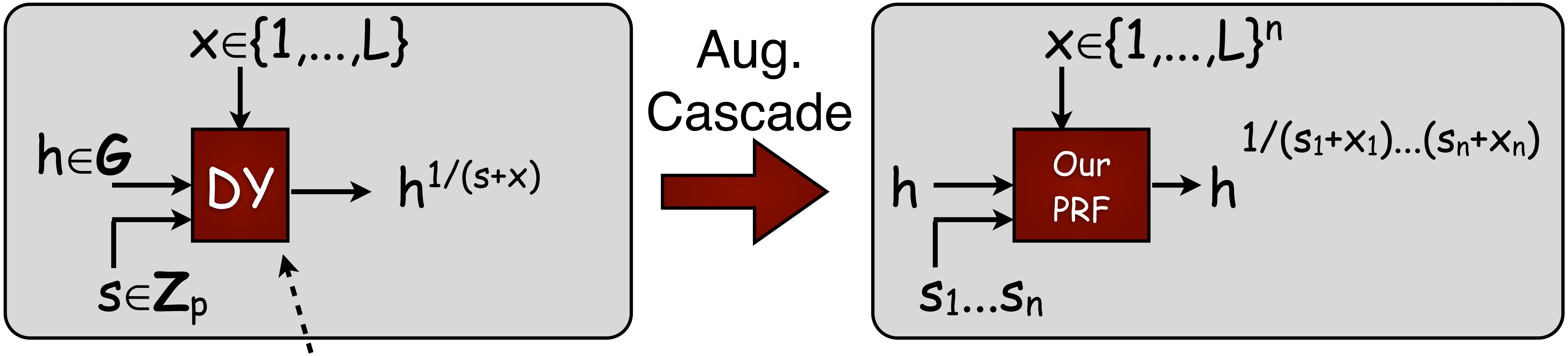

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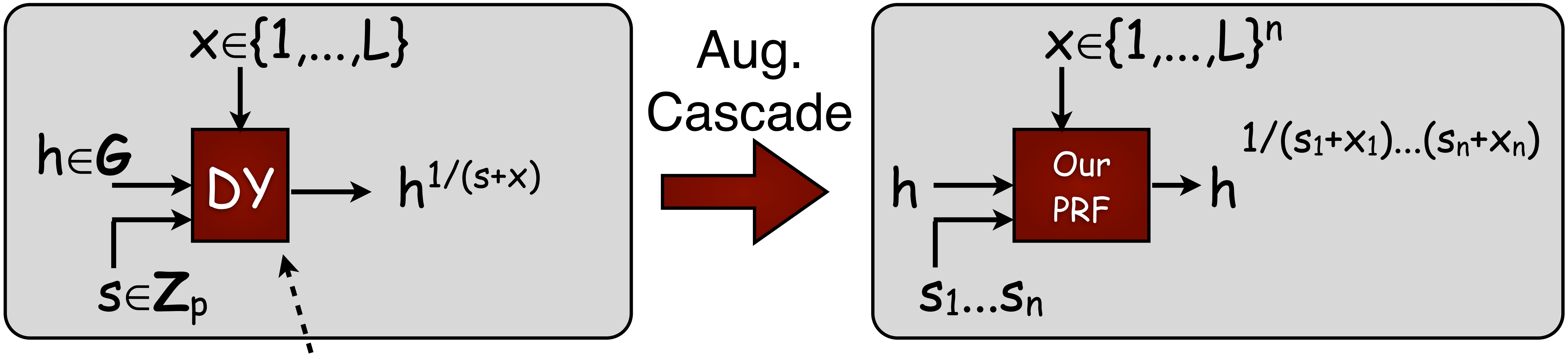

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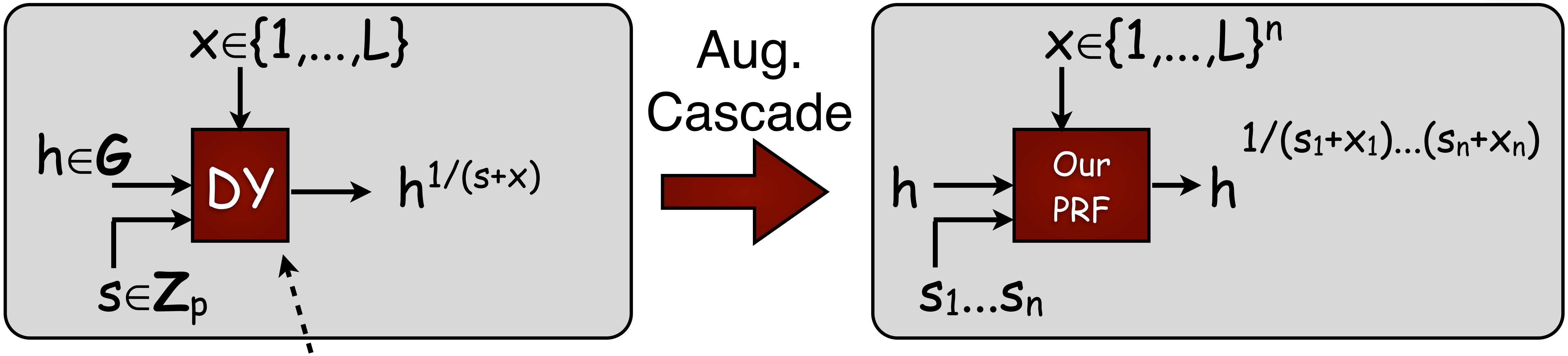
Theorem: DY is q-parallel secure under the L-DDH (inversion) assumption

New Algebraic PRF



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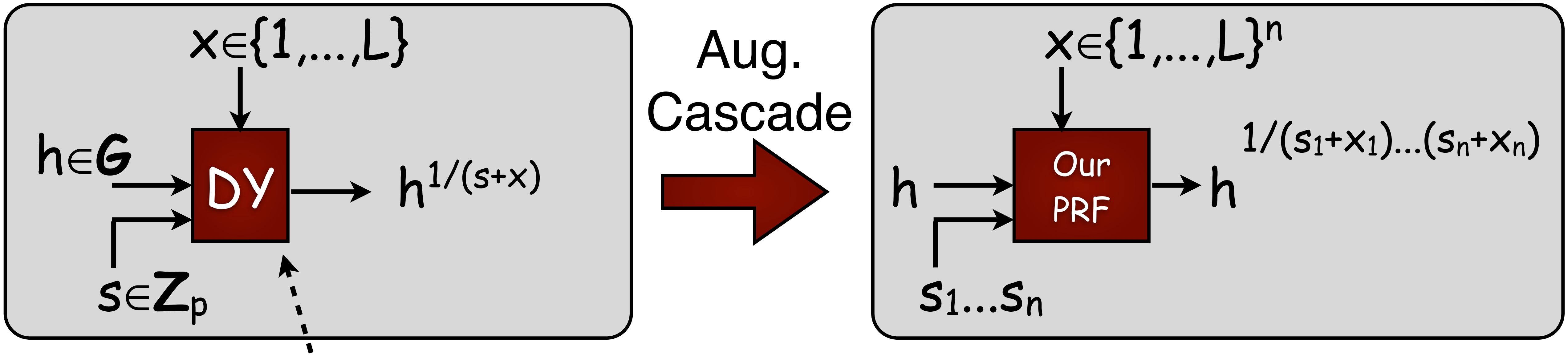
$g^{1/x}$ looks random in **G** given $(g, g^x, g^{x^2}, \ldots, g^{x^L})$

New Algebraic PRF



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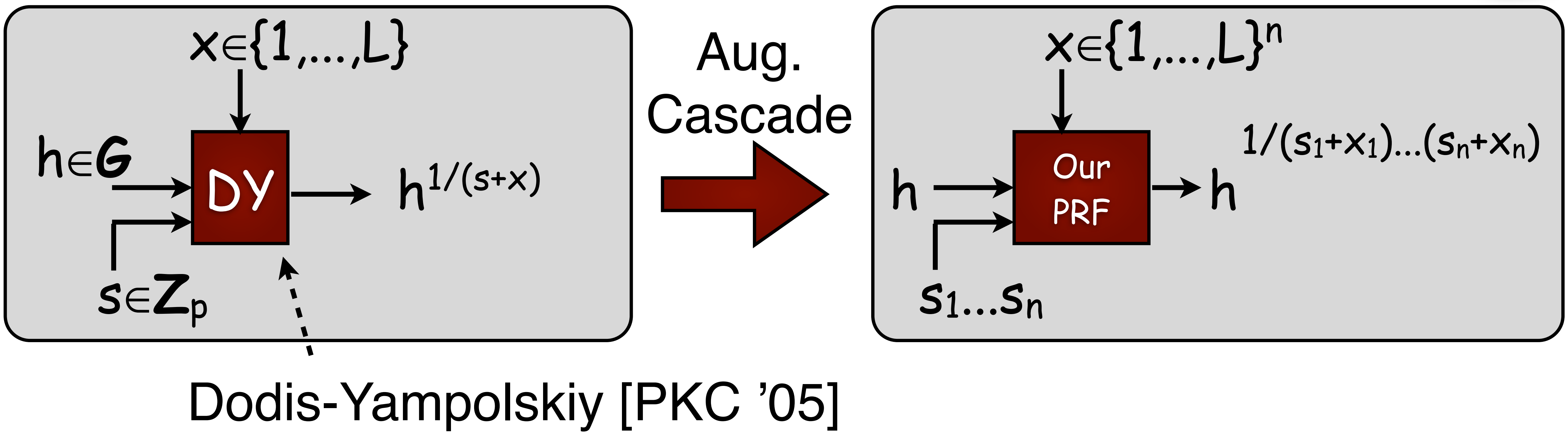
(Details in the paper)

New Algebraic PRF



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$g^{1/x}$ looks random in **G** given $(g, g^x, g^{x^2}, \ldots, g^{x^L})$

Corollary: Our PRF is secure PRF under the L-DDH assumption

Comparison to Naor-Reingold

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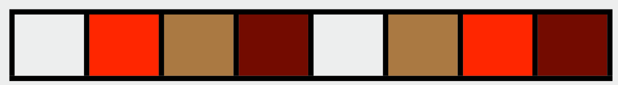
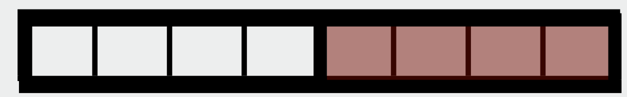
	Naor-Reingold PRF	Our PRF
Domain	$\{0,1\}^m$	$[L]^n$ ($L=2^l$, $n=m/l$)
Keys	h in $\mathbf{G}$, $x_1,\ldots,x_m$ in $\mathbf{Z}_p$	h in $\mathbf{G}$, $s_1,\ldots,s_n$ in $\mathbf{Z}_p$
PRF	 $\beta = x_1^{\square} . x_2^{\blacksquare} . x_3^{\blacksquare} . x_4^{\blacksquare} . x_5^{\square} . x_6^{\blacksquare} . x_7^{\blacksquare} . x_8^{\blacksquare}$ $F(x)=h^{\beta}$	 $\beta=(s_1 + \boxed{\square\square\square\square})(s_2+\boxed{\blacksquare\blacksquare\blacksquare\blacksquare})$ $F(x)=h^{1/\beta}$

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Secret key shorter by a factor of l

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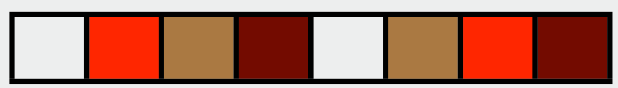
PRF	 $\beta = x_1.x_2.x_3.x_4.x_5.x_6.x_7.x_8$ $F(x)=h^{\beta}$	 $\beta=(s_1+\boxed{\square\square\square\square})(s_2+\boxed{\blacksquare\blacksquare\blacksquare\blacksquare})$ $F(x)=h^{1/\beta}$

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$l = 4$ or 8 is reasonable

Verifiable Random Functions

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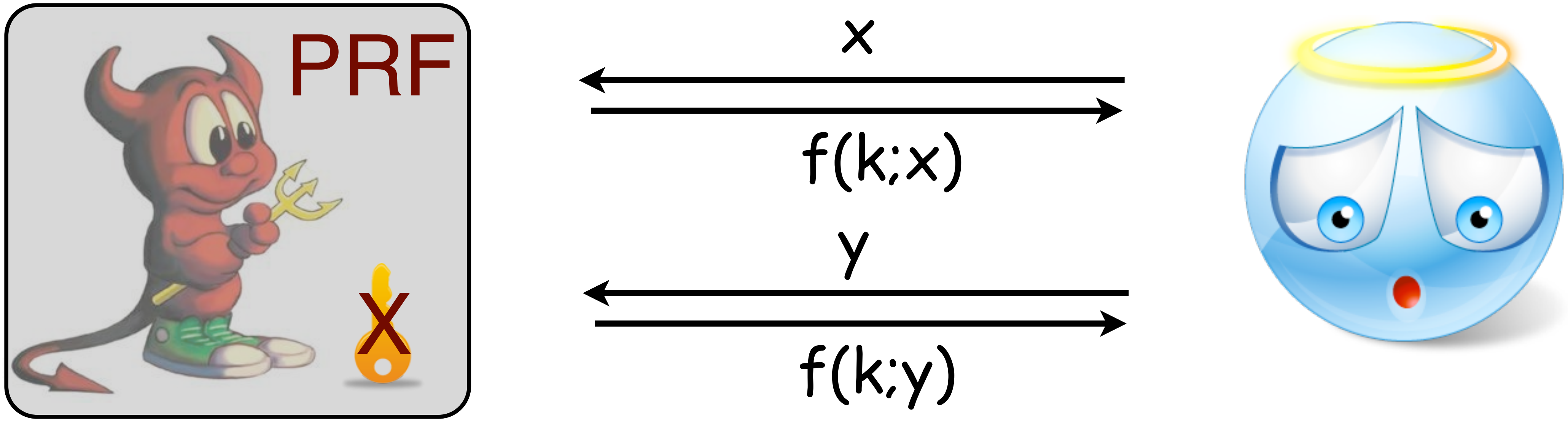
$\xleftarrow{x}$

$\xrightarrow[f(k;x)]{}$

$\xleftarrow{y}$

$\xrightarrow[f(k;y)]{}$

Verifiable Random Functions



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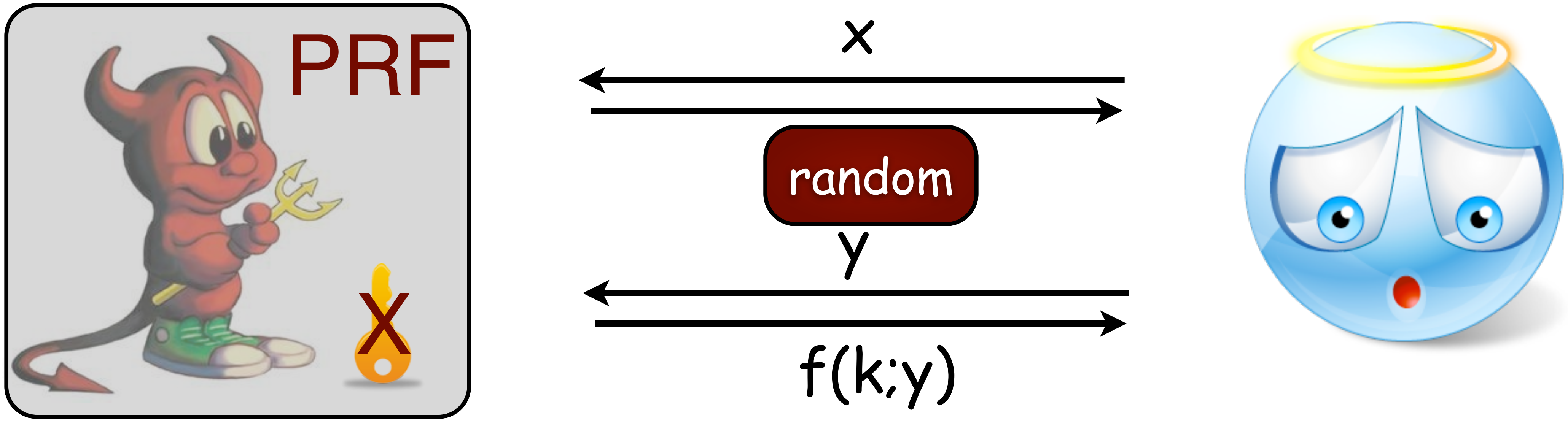

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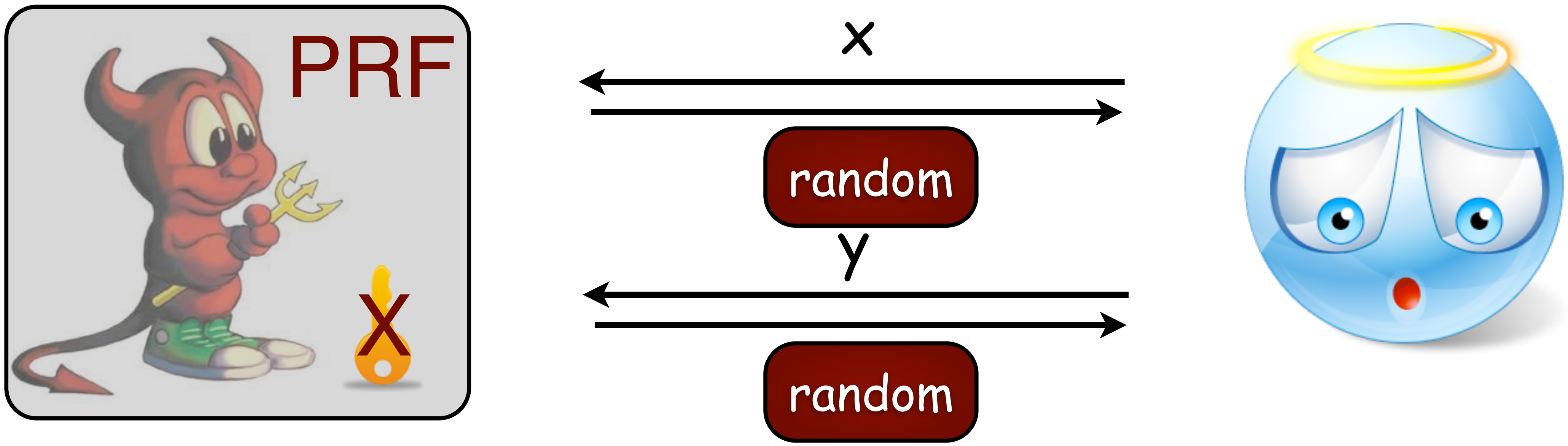

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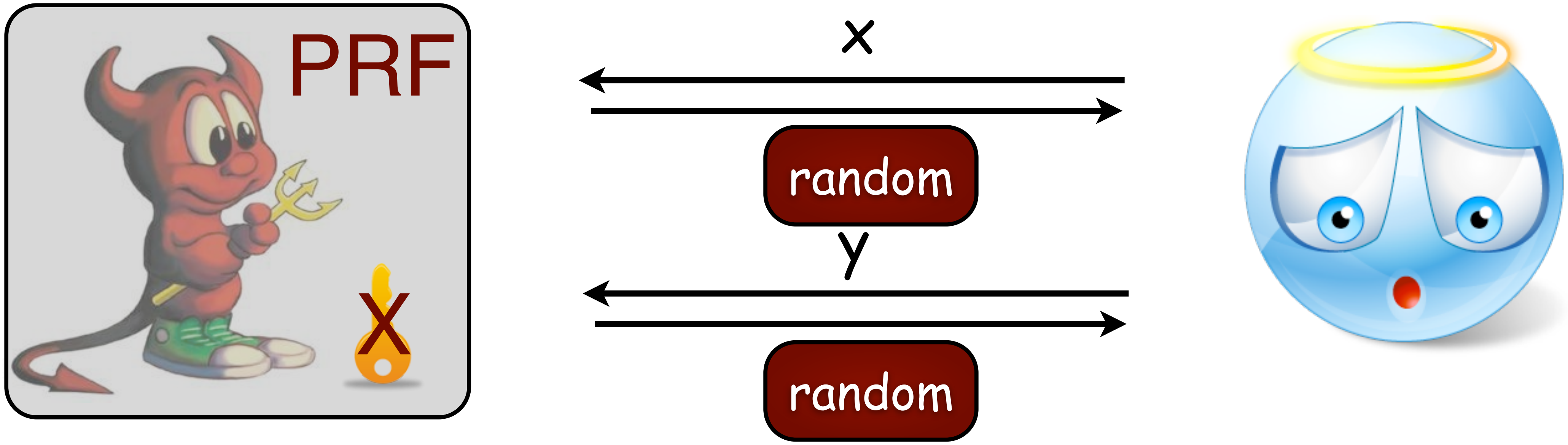
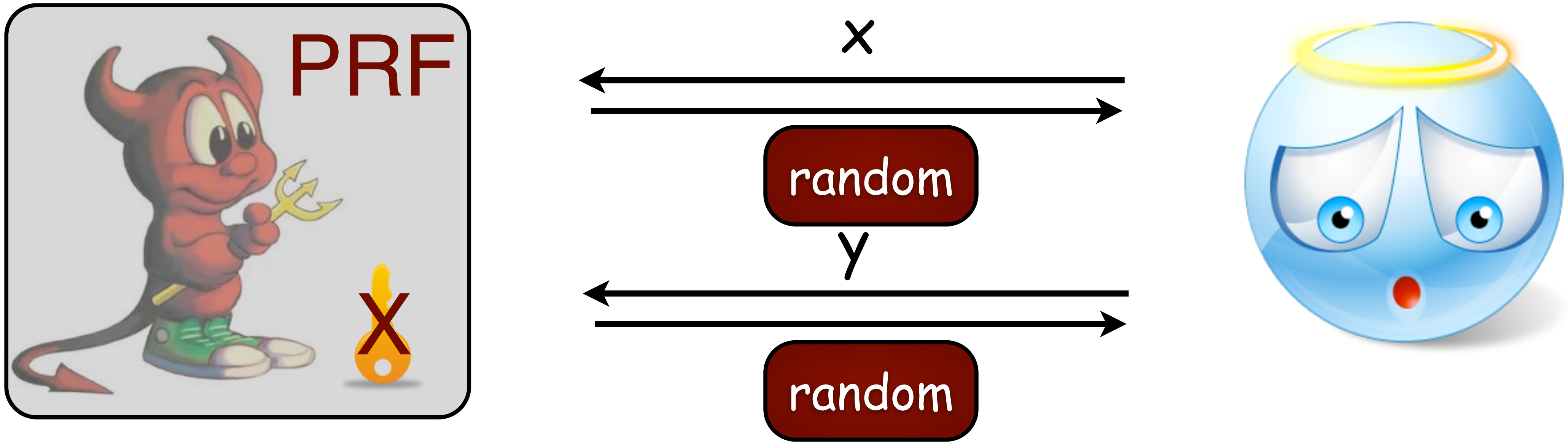


How to guarantee honest evaluation?

Verifiable Random Functions



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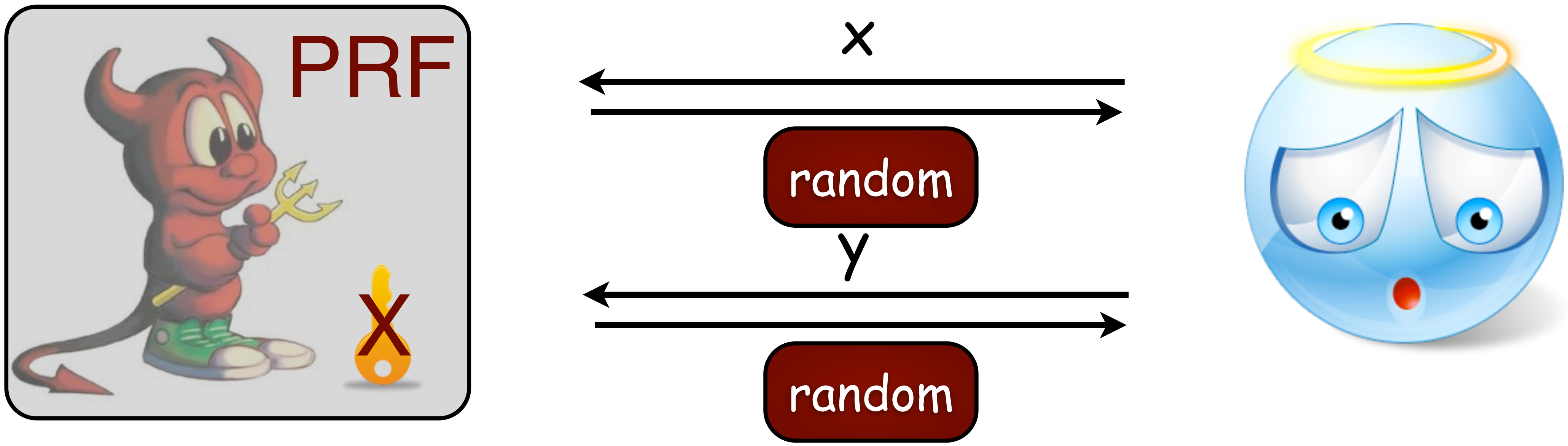

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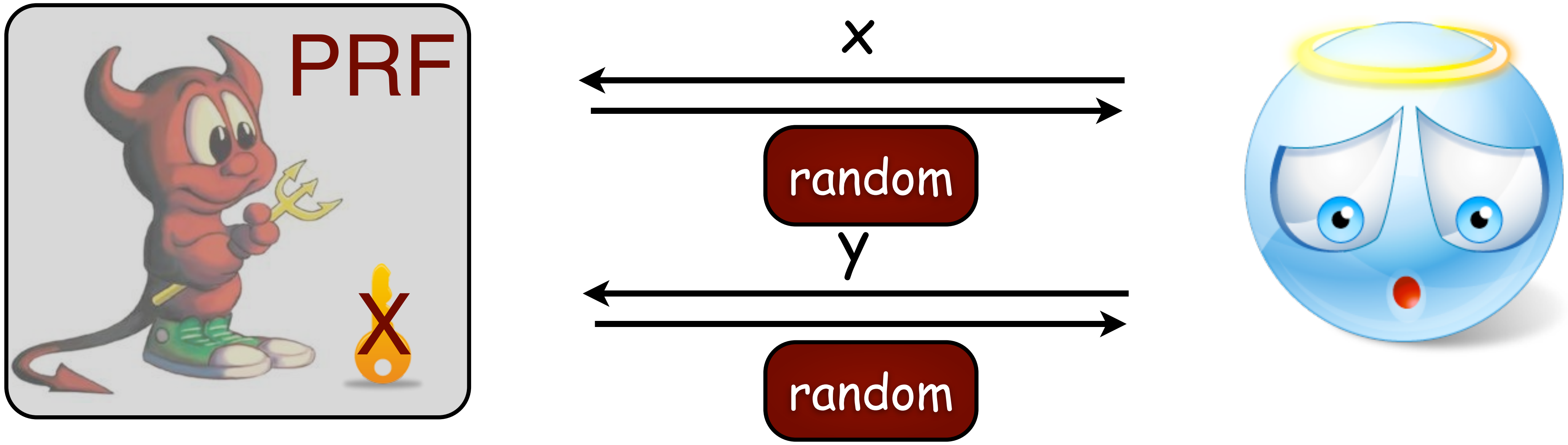

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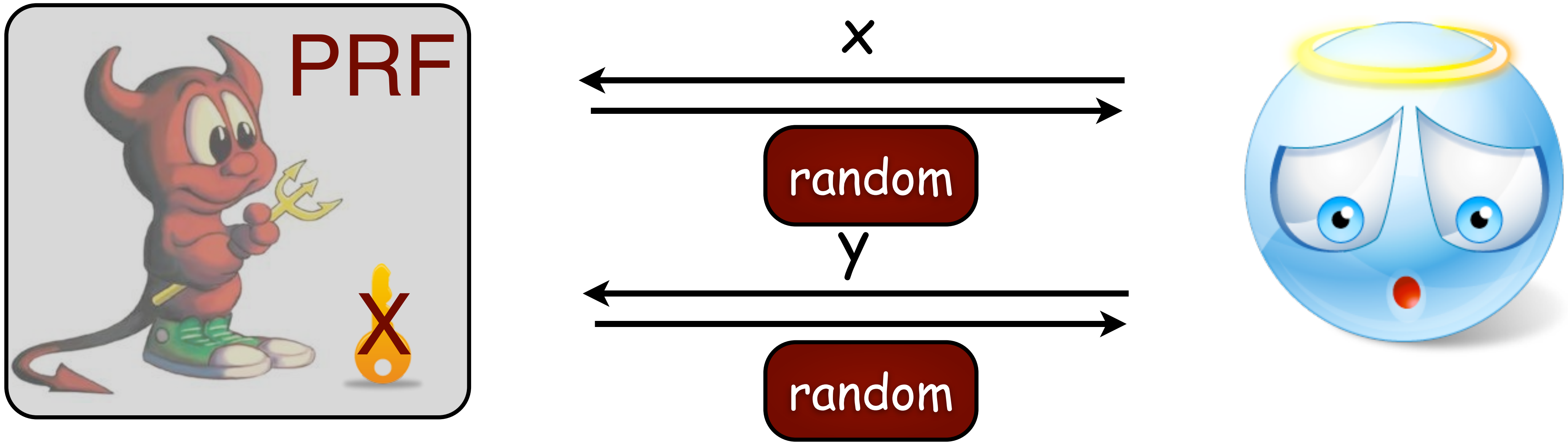

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- Applications: Unique-signature schemes, e-cash schemes [BCKL '09, ASM '07], updatable zero-knowledge databases [Liskov '05] etc.

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VRF	Domain Size	Assumption Size
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[HW '10]	2^m (arbitrary)	$O(mQ)$
our large-domain VRF	2^m (arbitrary)	$O(m)$

Conclusions

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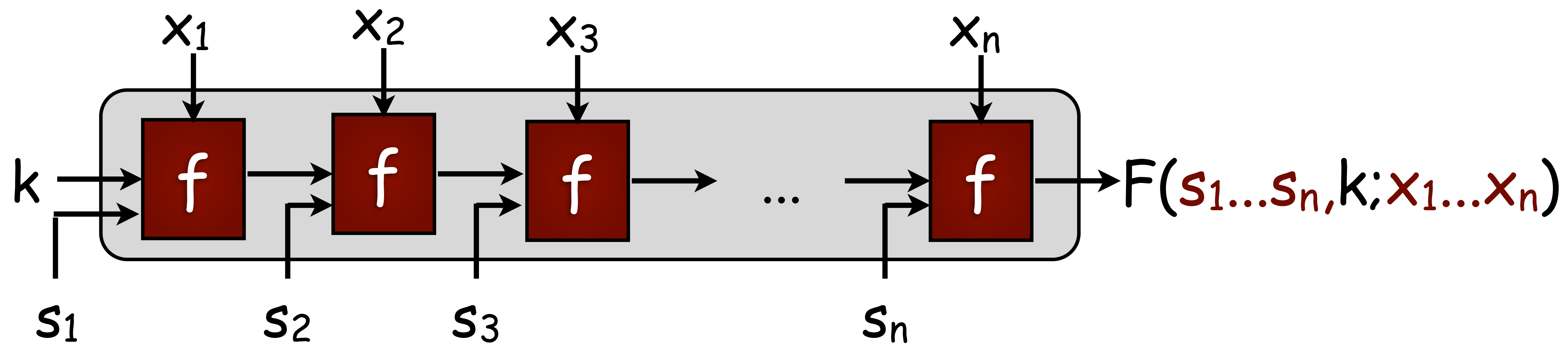

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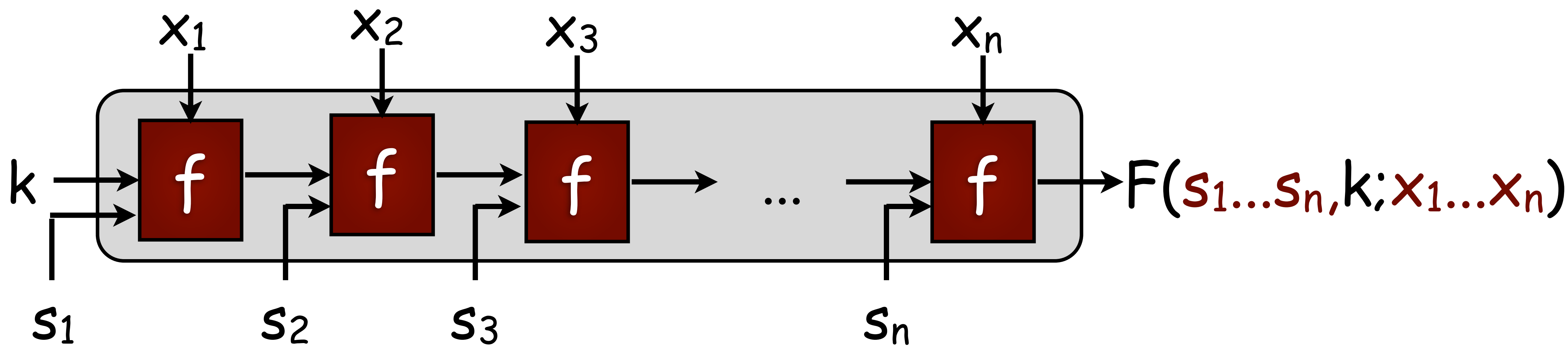

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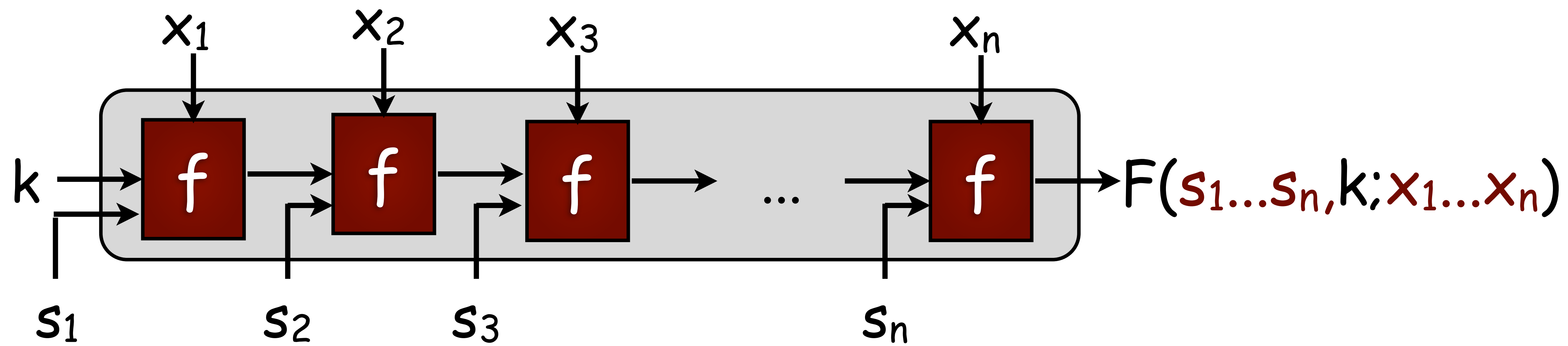

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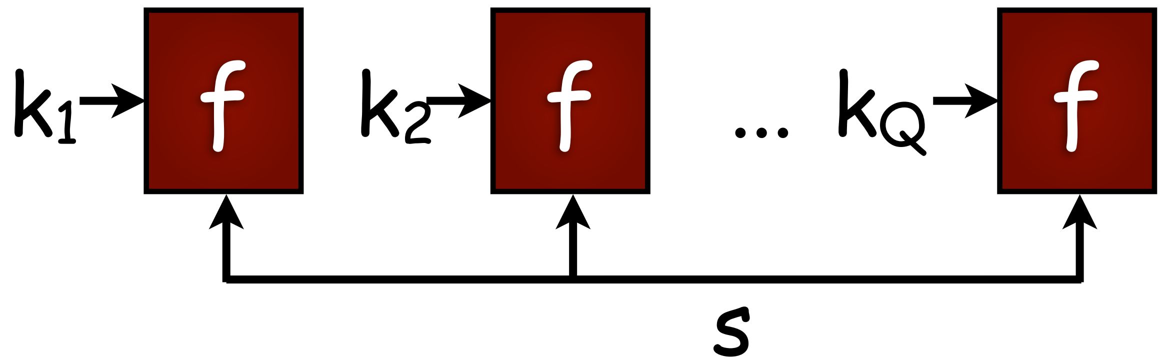

Conclusions

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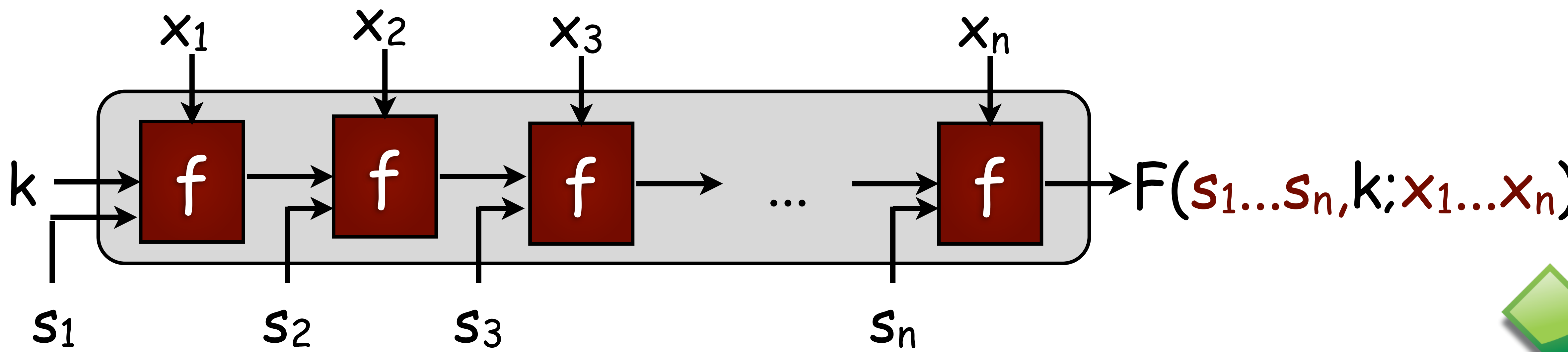
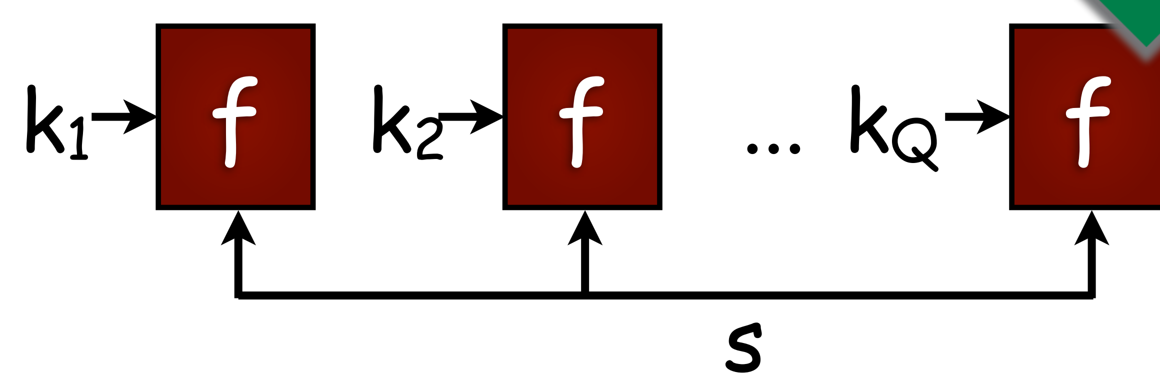


2) Simple proofs of security for existing algebraic PRFs



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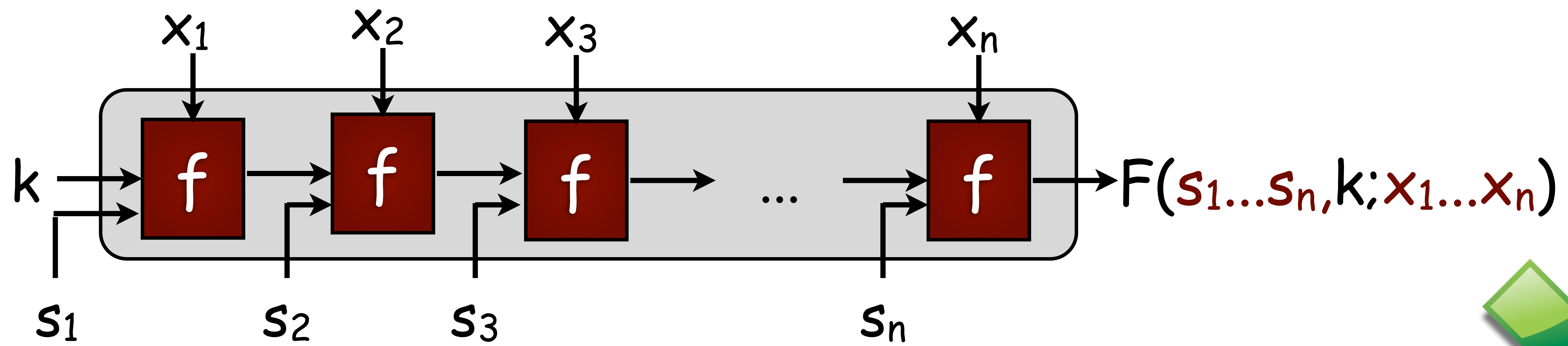

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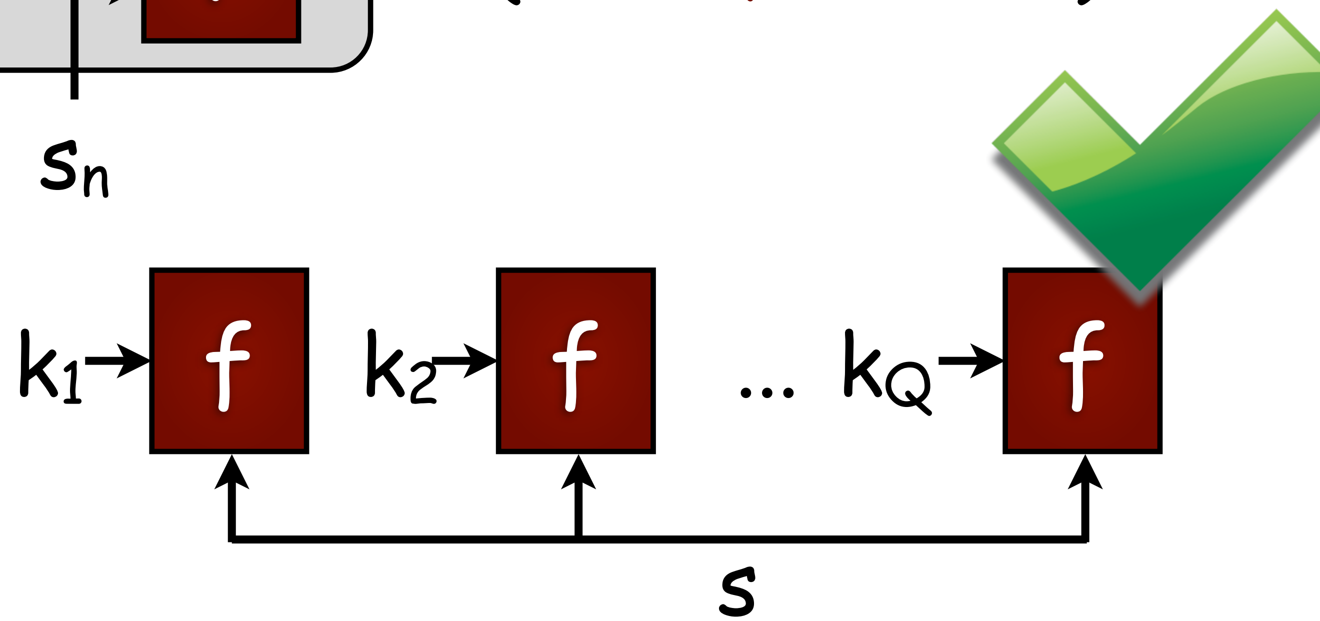
3) New efficient large-domain PRF



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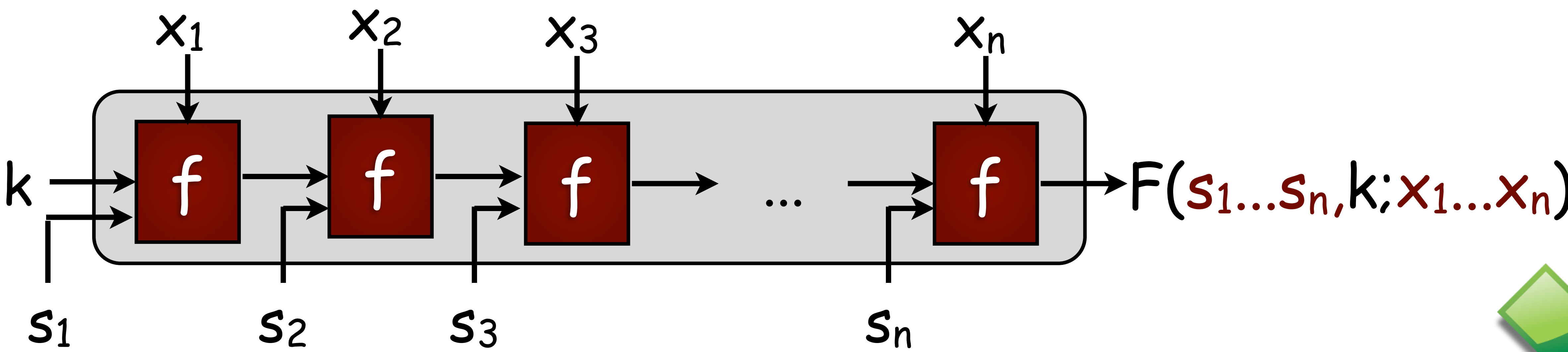

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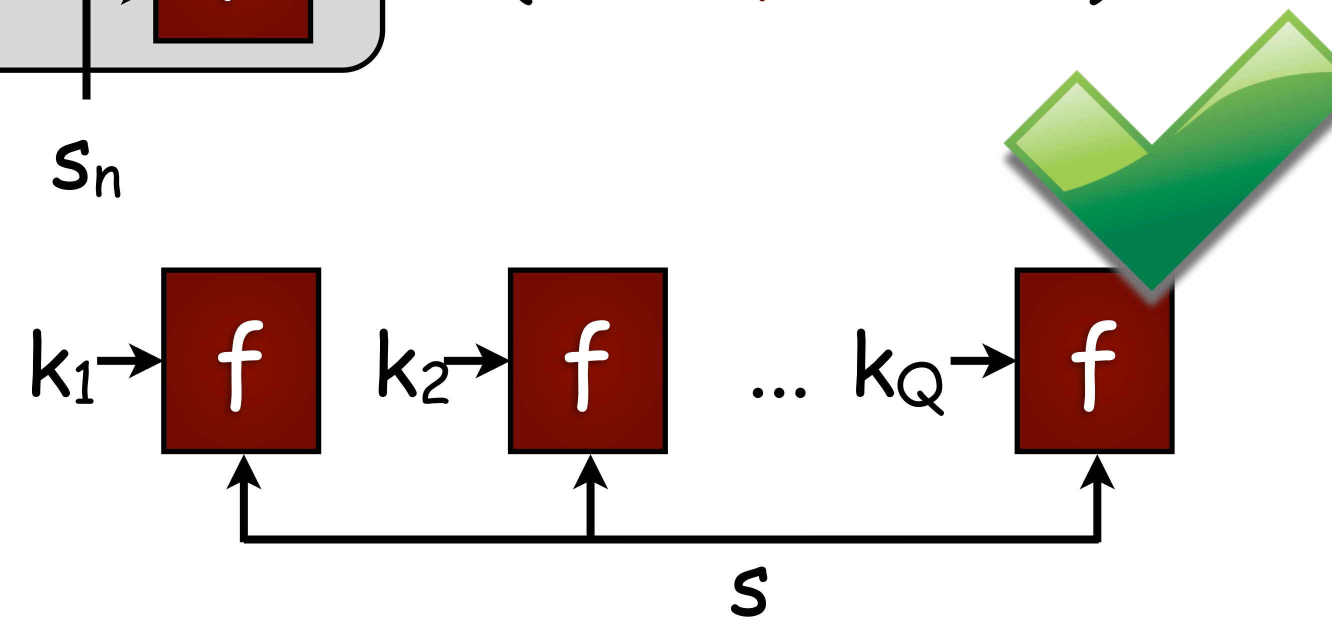

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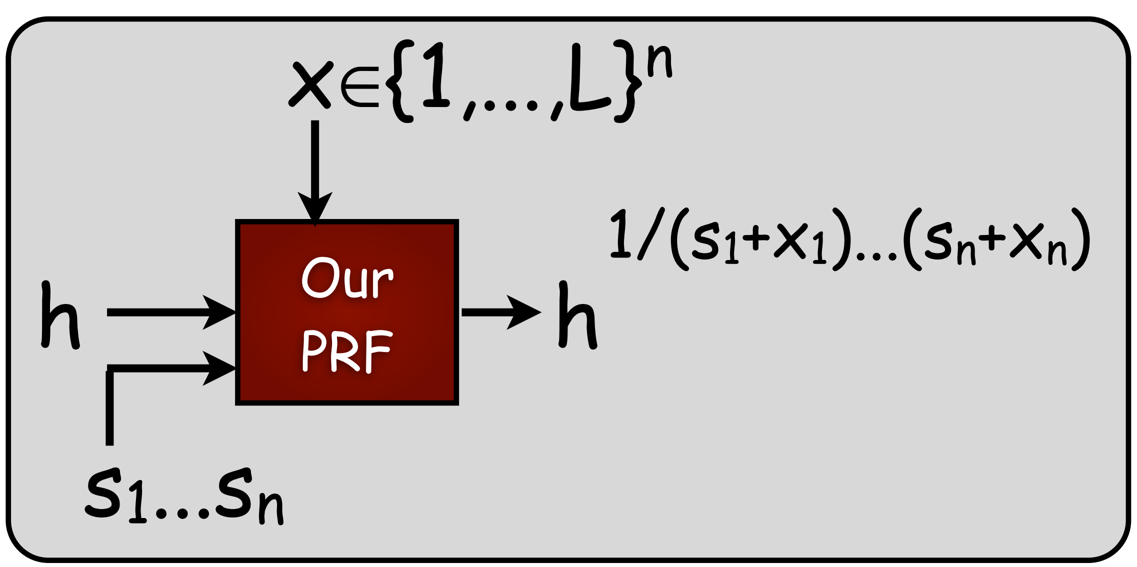

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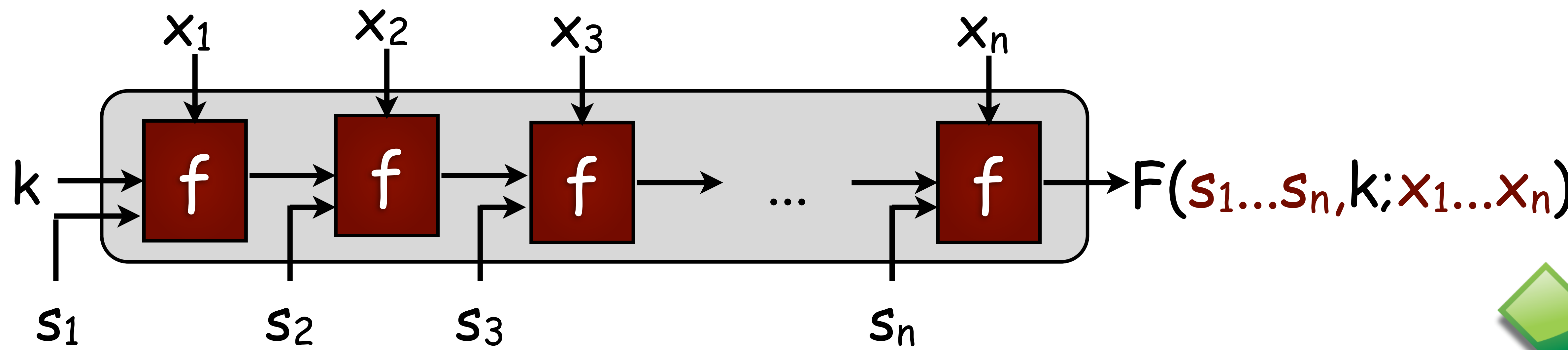

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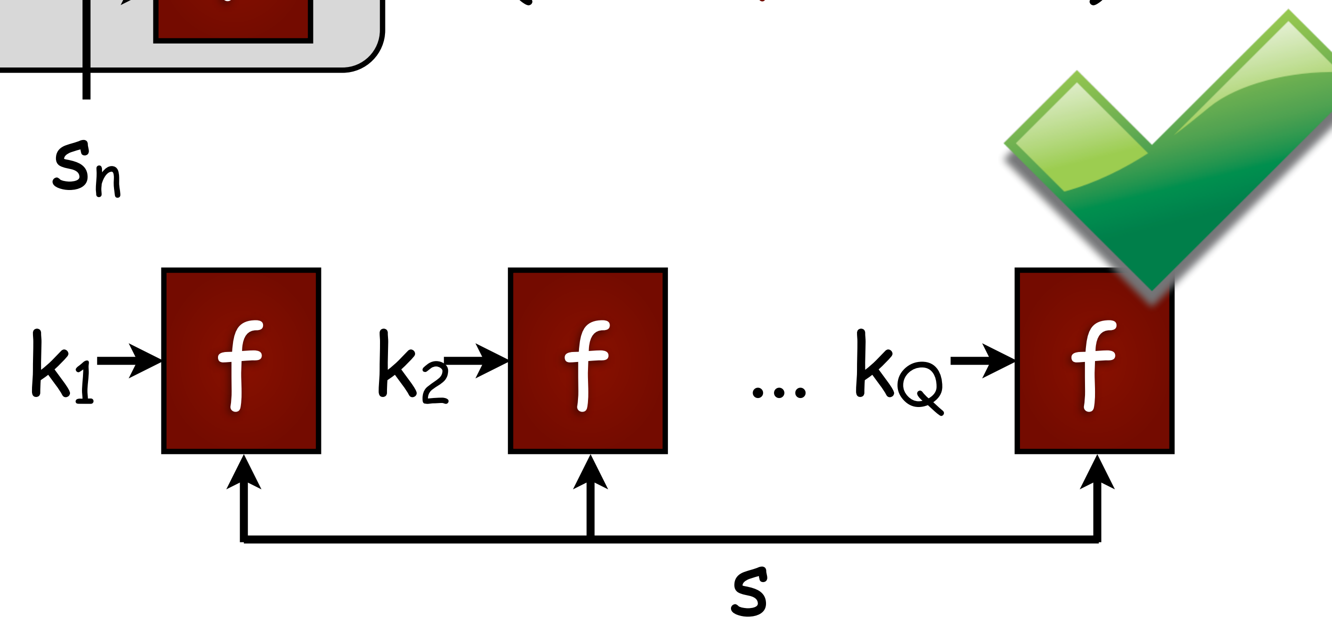

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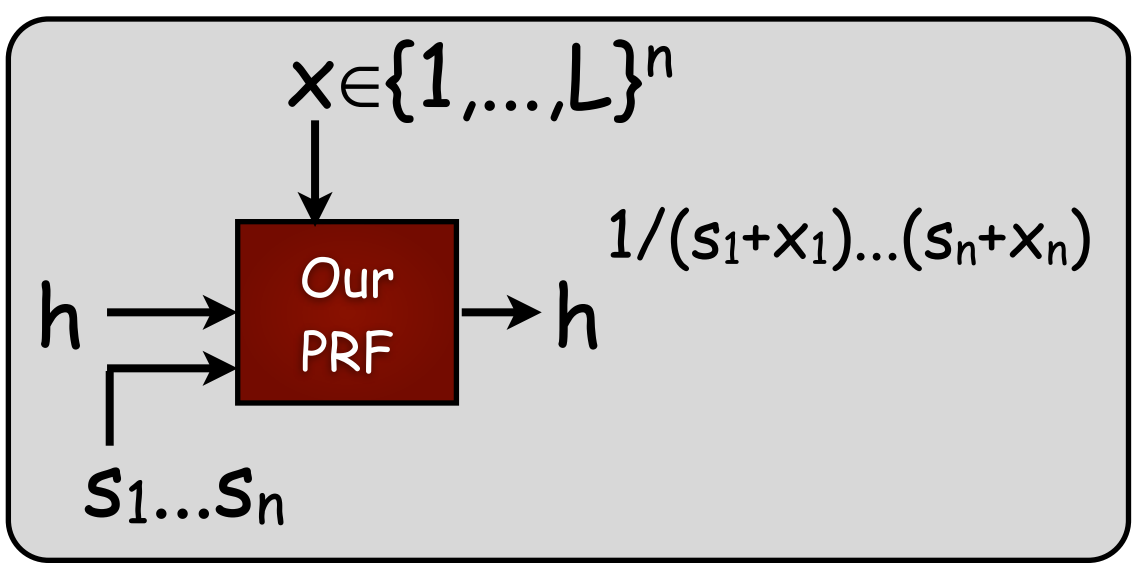

4) VRFs based on better security assumptions

Conclusions

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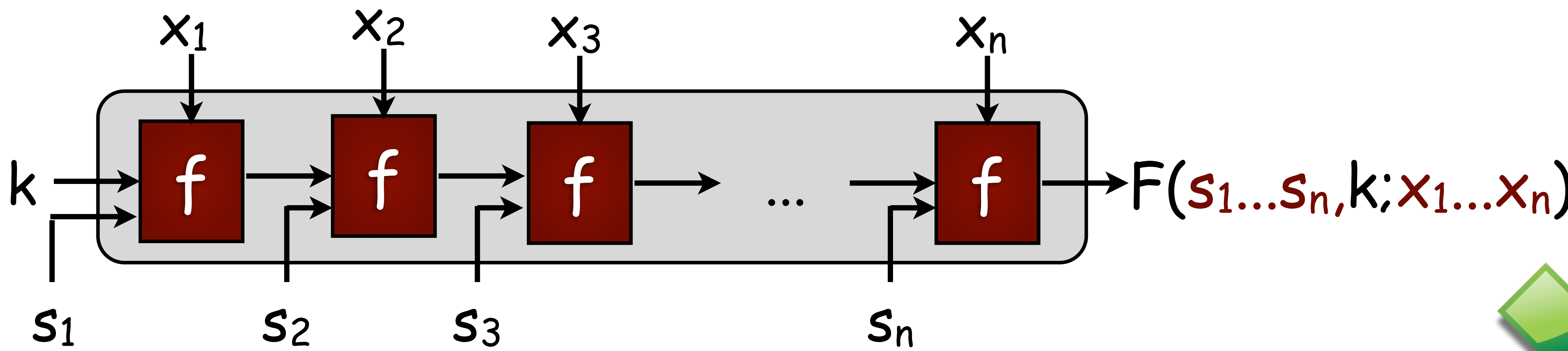

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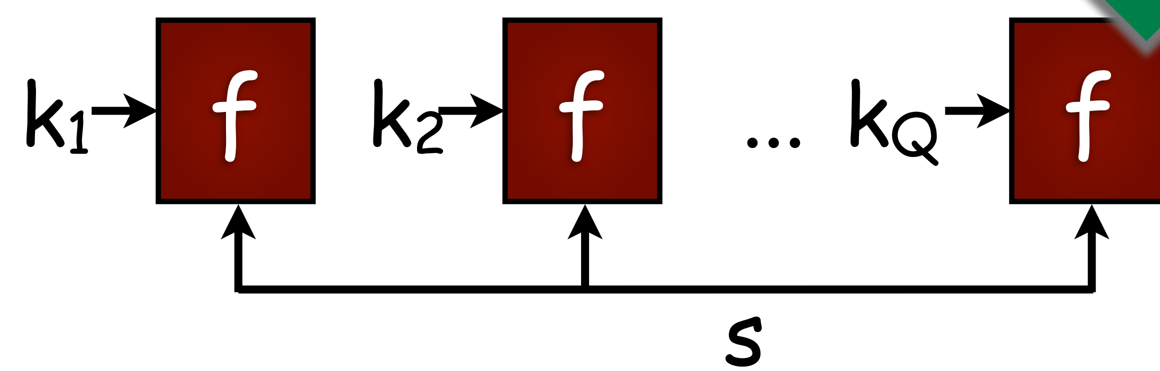

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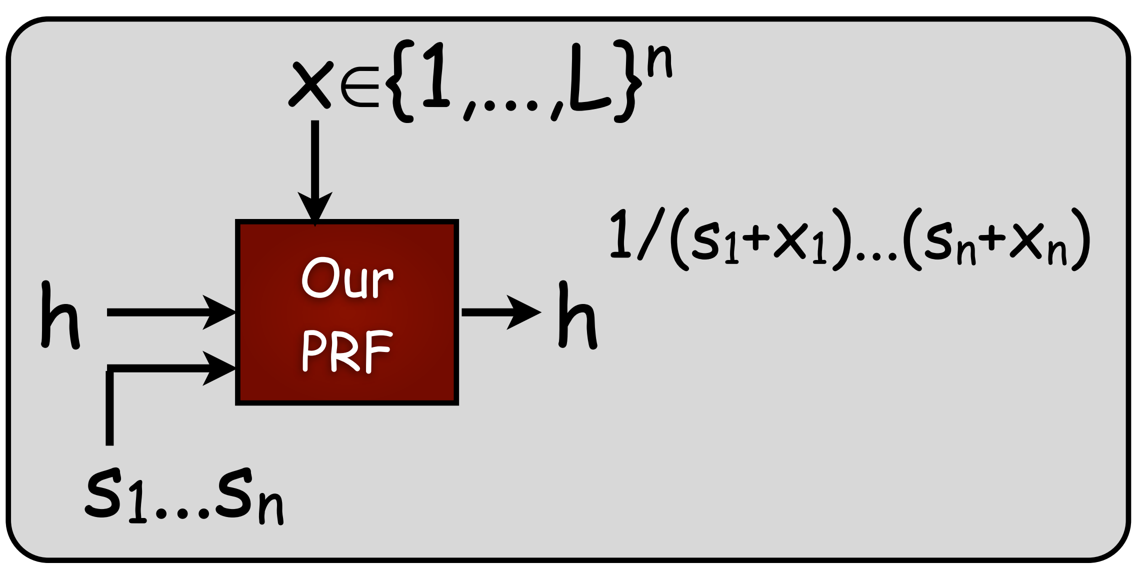

4) VRFs based on better security assumptions

5) (in paper) Simulatable VRFs

Thank You!

Any questions?