Failures of secret-key cryptography

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http://xkcd.com/538/
2011 Grigg–Gutmann (and again 2012 Gutmann): In the past 15 years “no one ever lost money to an attack on a properly designed cryptosystem (meaning one that didn’t use homebrew crypto or toy keys) in the Internet or commercial worlds”.
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2002 Shamir: “Cryptography is usually bypassed. I am not aware of any major world-class security system employing cryptography in which the hackers penetrated the system by actually going through the cryptanalysis.”
2013.03 Bernstein:

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Or are they simply wrong: real-world crypto is breakable; is in fact being broken; is one of many ongoing disaster areas in security?”
“Do these people mean that it’s actually infeasible to break real-world crypto? Or do they mean that breaks are feasible but still not worthwhile for the attackers? Or are they simply wrong: real-world crypto is breakable; is in fact being broken; is one of many ongoing disaster areas in security?”

Let’s look at some examples.
Windows code signatures

Flame broke into computers, spied on audio, keystrokes, etc.

2012.06.03 Microsoft:
“We recently became aware of a complex piece of targeted malware known as ‘Flame’ and immediately began examining the issue. . . . We have discovered through our analysis that some components of the malware have been signed by certificates that allow software to appear as if it was produced by Microsoft.”
2012.06.07 Stevens: “A chosen-prefix collision attack against MD5 has been used for Flame. More interestingly . . . not our published chosen-prefix collision attack was used, but an entirely new and unknown variant.”
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CrySyS: Flame file wavesup3.drv appeared in logs in 2007; Flame “may have been active for as long as five to eight years”.

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Was MD5 “homebrew crypto”? No. Standardized, widely used. Worthwhile to attack? Yes.
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WEP

WEP introduced in 1997 in 802.11 wireless standard.

2001 Borisov–Goldberg–Wagner: 24-bit “nonce” frequently repeats, leaking plaintext xor and allowing very easy forgeries.

2001 Arbaugh–Shankar–Wan: this also breaks user auth.

2001 Fluhrer–Mantin–Shamir: WEP builds RC4 key \((k, n)\) from secret \(k\), “nonce” \(n\); RC4 outputs leak bytes of \(k\).

“These are academic papers! Nobody was actually attacked.”

Fact: WEP blamed for 2007 theft of 45 million credit-card numbers from T. J. Maxx. Subsequent lawsuit settled for $409000000.
Keeloq

Wikipedia: “KeeLoq is or was used in many remote keyless entry systems by such companies as Chrysler, Daewoo, Fiat, GM, Honda, Toyota, Volvo, Volkswagen Group, Clifford, Shurlok, Jaguar, etc.”

2007 Indesteege–Keller–Biham–Dunkelman–Preneel

“How to steal cars”: recover 64-bit KeeLoq key using $2^{16}$ known plaintexts, only $2^{44.5}$ encryptions.

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2. If all the “X is weak” press comes from academics, is it safe to conclude that real attackers aren’t breaking X? How often do real attackers issue press releases?
VMWare View

VMWare View is a remote desktop protocol supported by many low-cost terminals.

Recommendation from VMWare, Dell, etc.: switch from “AES-128” to “SALSA20-256” for the “best user experience”. Apparently AES slows down network graphics.
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Closer look at documentation: “AES-128” and “SALSA20-256” are actually “AES-128-GCM” and “Salsa20-256-Round12”.
AES-128-GCM includes AES and message authentication.

No indication that VMWare’s “Salsa20-256-Round12” includes any message authentication. Can attacker forge packets? One can easily combine Salsa20 with message authentication, but does VMWare do this?

Salsa20 has speed and security advantages over AES, but both Salsa20 and AES are unauthenticated ciphers. User needs authenticated cipher.
SSL/TLS/HTTPS

Standard AES-CBC encryption of a packet \((p_0, p_1, p_2)\):
send random \(v\),
\[c_0 = \text{AES}_k(p_0 \oplus v),\]
\[c_1 = \text{AES}_k(p_1 \oplus c_0),\]
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\]

AES-CBC encryption in SSL:

retrieve last block \(c_{-1}\) from previous ciphertext; send

\[
c_0 = \text{AES}_k(p_0 \oplus c_{-1}),
\]

\[
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\]

\[
c_2 = \text{AES}_k(p_2 \oplus c_1).
\]
SSL lets attacker choose $p_0$ as function of $c_{-1}$! Very bad.

**2002 Möller:**
To check a guess $g$ for (e.g.) $p_{-3}$, choose $p_0 = c_{-1} \oplus g \oplus c_{-4}$, compare $c_0$ to $c_{-3}$.

**2006 Bard:**
malicious code in browser should be able to carry out this attack, especially if high-entropy data is split across blocks.

**2011 Duong–Rizzo “BEAST”:**
fast attack fully implemented, including controlled variable split.
Countermeasure in browsers:
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2013.02 AlFardan–Paterson “Lucky 13”: watch timing more closely; attack still works.
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The software does support one non-CBC option:
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The software does support one non-CBC option: RC4. 2013.01: widely recommended, used for 50% of SSL traffic.
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Problem: many nasty biases in RC4 output bytes $z_1, z_2, \ldots$.
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2001 Rivest: “The new attacks do not apply to RC4-based SSL.
... [protocol] designers [using RC4] should not be concerned.”

Problem: many nasty biases in RC4 output bytes $z_1, z_2, \ldots$

The single-byte biases:

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But wait: there’s more!
accurately computed $\Pr[z_i = j]$ for all $i \in \{1, \ldots, 256\}$, all $j$; found $\approx 65536$ single-byte biases; used all of them in SSL attack via proper Bayesian analysis.
2013 AlFardan–Bernstein–Paterson–Poettering–Schuldt: *accurately* computed $\Pr[z_i = j]$ for all $i \in \{1, \ldots, 256\}$, all $j$; found $\approx 65536$ single-byte biases; used *all* of them in SSL attack via proper Bayesian analysis.

$\approx 256$ of these biases were found independently (slightly earlier) by 2013 Watanabe–Isobe–Ohigashi–Morii, 2013 Isobe–Ohigashi–Watanabe–Morii: $z_{32} \rightarrow 224$, $z_{48} \rightarrow 208$, etc.; $z_3 \rightarrow 131$; $z_i \rightarrow i$; $z_{256} \not\rightarrow 0$. 
Graph of $256 \Pr[z_1 = x]$: 

![Graph of 256 Pr[z_1 = x]](image-url)
Graph of $256 \Pr[z_2 = x]$:
Graph of $256 \Pr[z_3 = x]$: 
Graph of $256 \Pr[z_4 = x]$:
Graph of $256 \Pr[z_5 = x]$:
Graph of $256 \Pr[z_6 = x]$:
Graph of 256 $\Pr[z_7 = x]$:
Graph of $256 \Pr[z_8 = x]$: 
Graph of $256 \Pr[z_9 = x]$: 
Graph of 256 $\Pr[z_{10} = x]$: 

![Graph of 256 Pr[z_{10} = x]](image-url)
Graph of $256 \Pr[z_{11} = x]$: 
Graph of $256 \Pr[z_{12} = x]$: 
Graph of $256 \Pr[z_{13} = x]$: 
Graph of $256 \Pr[z_{14} = x]$:
Graph of $256 \Pr[z_{15} = x]$:
Graph of $256 \text{ Pr}[x_{16} = x]$: 
Graph of $256 \Pr[z_{17} = x]$: 

![Graph of $256 \Pr[z_{17} = x]$](image-url)
Graph of $256 \Pr[z_{18} = x]$:
Graph of $256 \Pr[z_{19} = x]$: 
Graph of $256 \Pr[z_{20} = x]$: 

![Graph of $256 \Pr[z_{20} = x]$](image-url)
Graph of 256 $Pr[z_{21} = x]$:
Graph of $256 \Pr[z_{22} = x]$:
Graph of $256 \Pr[z_{23} = x]$: 
Graph of $256 \Pr[z_{24} = x]$: 

![Graph of $256 \Pr[z_{24} = x]$](image-url)
Graph of $256 \Pr[z_{25} = x]$:
Graph of $256 \Pr[z_{26} = x]$:
Graph of 256 $\Pr[z_{27} = x]$: 

![Graph of 256 Pr[z_{27} = x]]
Graph of $256 \Pr[z_{28} = x]$: 
Graph of 256 $\Pr[z_{29} = x]$: 
Graph of $256 \Pr[z_{30} = x]$:
Graph of $256 \text{Pr}[z_{31} = x]$: 

![Graph of 256 Pr[z_{31} = x]]
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Graph of $256 \text{Pr}[z_{40} = x]$: 
Graph of $256 \Pr[z_{41} = x]$: 

![Graph of 256 Pr[z_{41} = x]](image)
Graph of $256 \Pr[z_{42} = x]$: 

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Graph of 256 Pr[\(z_{43} = x\)]:
Graph of $256 \Pr[z_{44} = x]$:
Graph of $256 \text{Pr}[z_{45} = x]$: 
Graph of $256 \Pr[z_{46} = x]$: 

![Graph](image-url)
Graph of $256 \Pr[z_{47} = x]$:
Graph of $256 \Pr[z_{48} = x]$:
Graph of $256 \Pr[z_{49} = x]$: 

![Graph of 256 Pr[z_{49} = x]](image-url)
Graph of $256 \Pr[z_{50} = x]$:
Graph of $256 \operatorname{Pr}[x_{51} = x]$: 

![Graph of 256 Pr[x_{51} = x]](image-url)
Graph of $256 \Pr[z_{52} = x]$: 

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Graph of $256 \Pr[z_{58} = x]$: 

![Graph of $256 \Pr[z_{58} = x]$](image)
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Graph of $256 \Pr[z_{73} = x]$: 

![Graph](image-url)
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Graph of $256 \Pr[z_{81} = x]$: 
Graph of 256 $\Pr[z_{82} = x]$: 

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Graph of $256 \Pr[z_{83} = x]$:
Graph of $256 \Pr[z_{84} = x]$:
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Graph of 256 $\Pr[z_{88} = x]$: 

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Graph of $256 \Pr[z_{91} = x]$:
Graph of $256 \Pr[z_{92} = x]$: 
Graph of $256 \Pr[z_{93} = x]$:
Graph of $\text{Pr}[z_{94} = x]$: 

![Graph of $\text{Pr}[z_{94} = x]$]
Graph of $256 \text{Pr}[z_{95} = x]$: 

![Graph of probability distribution](https://via.placeholder.com/150)
Graph of $256 \Pr[z_{96} = x]$: 

![Graph of $256 \Pr[z_{96} = x]$](image-url)
Graph of $256 \Pr[z_{97} = x]$: 

![Graph of $256 \Pr[z_{97} = x]$]
Graph of $256 \Pr[z_{98} = x]$: 
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Graph of $256 \text{Pr}[z_{102} = x]$: 

![Graph of 256 Pr[z_{102} = x]](image-url)
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![Graph of $256 \Pr[z_{105} = x]$](image-url)
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Graph of $256 \text{Pr}[z_{113} = x]$: 

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Graph of $256 \Pr[z_{115} = x]$:
Graph of $256 \Pr[z_{116} = x]$: 

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Graph of $256 \Pr[z_{117} = x]$:
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Graph of $256 \Pr[z_{119} = x]$:
Graph of 256 $\Pr[z_{120} = x]$:
Graph of $256 \Pr[z_{121} = x]$: 

![Graph of $256 \Pr[z_{121} = x]$](image-url)
Graph of $256 \text{Pr}[z_{122} = x]$: 

![Graph of probability distribution for $256 \text{Pr}[z_{122} = x]$]
Graph of $256 \Pr[z_{123} = x]$: 

![Graph of 256 Pr[z_{123} = x]]
Graph of $256 \Pr[z_{124} = x]$: 

![Graph of $256 \Pr[z_{124} = x]$](image_url)
Graph of $256 \Pr[z_{125} = x]$:
Graph of $256 \Pr[z_{126} = x]$:
Graph of $256 \, \text{Pr}[z_{127} = x]$:
Graph of $256 \Pr[z_{128} = x]$:
Graph of $256 \Pr[z_{129} = x]$: 

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Graph of $256 \Pr[z_{133} = x]$: 
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Graph of $256 \Pr[z_{135} = x]$:
Graph of \( \Pr[z_{136} = x] \):
Graph of $256 \Pr[x_{137} = x]$: 

![Graph of $256 \Pr[x_{137} = x]$](image)
Graph of 256 Pr$[z_{138} = x]$: 
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![Graph of 256 Pr[z_{144} = x]](image-url)
Graph of $256 \Pr[\varepsilon_{145} = x]$: 

![Graph of $256 \Pr[\varepsilon_{145} = x]$](image)
Graph of $256 \Pr[\mathbf{z}_{146} = x]$:
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Graph of $256 \Pr[z_{151} = x]$: 
Graph of $256 \Pr[z_{152} = x]$:
Graph of $256 \Pr[z_{153} = x]$:
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![Graph of $256 \Pr[z_{157} = x]$](image.png)
Graph of $256 \Pr[z_{158} = x]$:
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Graph of $256 \Pr[z_{160} = x]$: 

![Graph of 256 Pr[z_{160} = x]](image-url)
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Graph of $256 \Pr[z_{202} = x]$:
Graph of $256 \Pr[z_{203} = x]$: 
Graph of $256 \Pr[z_{204} = x]$:
Graph of $256 \Pr[z_{205} = x]$:
Graph of $256 \Pr[z_{206} = x]$: 

![Graph of $256 \Pr[z_{206} = x]$](image)


Graph of $256 \Pr[z_{207} = x]$:
Graph of $256 \Pr[z_{208} = x]$:
Graph of $256 \Pr[z_{209} = x]$:
Graph of $256 \Pr[z_{210} = x]$:
Graph of $256 \Pr[z_{211} = x]$:
Graph of $256 \Pr[z_{212} = x]$:
Graph of $256 \Pr[z_{213} = x]$: 
Graph of $256 \Pr[z_{214} = x]$:
Graph of $256 \Pr[z_{215} = x]$: 

![Graph of $256 \Pr[z_{215} = x]$](image-url)
Graph of $256 \Pr[\sigma_{216} = x]$: 
Graph of $256 \Pr[z_{217} = x]$: 

![Graph of 256 Pr[z_{217} = x]](image-url)
Graph of $256 \Pr[z_{218} = x]$: 

![Graph of $256 \Pr[z_{218} = x]$](image-url)
Graph of $256 \Pr[\mathcal{Z}_{219} = x]$: 

![Graph of $256 \Pr[\mathcal{Z}_{219} = x]$](image_url)
Graph of 256 $\Pr[z_{220} = x]$:
Graph of $\Pr[z_{221} = x]$:
Graph of $256 \Pr[z_{222} = x]$:
Graph of $256 \Pr[z_{223} = x]$:  

![Graph of $256 \Pr[z_{223} = x]$](image)
Graph of $256 \Pr[z_{224} = x]$: 

![Graph of $256 \Pr[z_{224} = x]$](image)
Graph of $256 \Pr[z_{225} = x]$:
Graph of $256 \Pr[z_{226} = x]$: 

![Graph](https://via.placeholder.com/150)
Graph of $256 \Pr[z_{227} = x]$:
Graph of $256 \Pr[\mathcal{z}_{228} = x]$: 

![Graph of $256 \Pr[\mathcal{z}_{228} = x]$]
Graph of $256 \Pr[z_{229} = x]$:
Graph of 256 $\Pr[z_{230} = x]$: 

![Graph of $\Pr[z_{230} = x]$](image-url)
Graph of $256 \Pr[z_{231} = x]$: 

![Graph of 256 Pr[z_{231} = x]](image-url)
Graph of $256 \Pr[z_{232} = x]$: 

![Graph of $256 \Pr[z_{232} = x]$](image-url)
Graph of $256 \Pr[z_{233} = x]$: 
Graph of $256 \Pr[z_{234} = x]$:
Graph of $256 \Pr[z_{235} = x]$:
Graph of $256 \Pr[z_{236} = x]$:
Graph of $\Pr[z_{237} = x]$:
Graph of $256 \Pr[z_{238} = x]$:
Graph of $256 \Pr[z_{239} = x]$: 

![Graph of $256 \Pr[z_{239} = x]$](image)
Graph of $256 \Pr[z_{240} = x]$:
Graph of $256 \Pr[z_{241} = x]$: 

![Graph of 256 Pr[z_{241} = x]](image-url)
Graph of $256 \Pr[z_{242} = x]$: 

![Graph of $256 \Pr[z_{242} = x]$](image-url)
Graph of 256 \( \Pr[z_{243} = x] \):
Graph of $256 \Pr[z_{244} = x]$:
Graph of $256 \Pr[z_{245} = x]$: 

![Graph of $256 \Pr[z_{245} = x]$](image-url)
Graph of $256 \Pr[z_{246} = x]$:
Graph of $256 \Pr[z_{247} = x]$: 

![Graph](image-url)
Graph of $256 \Pr[z_{248} = x]$: 
Graph of 256 $\Pr[z_{249} = x]$: 

![Graph of 256 $\Pr[z_{249} = x]$](image-url)
Graph of $256 \Pr[z_{250} = x]$:
Graph of $256 \Pr[z_{251} = x]$: 

![Graph of $256 \Pr[z_{251} = x]$](image-url)
Graph of $256 \Pr[z_{252} = x]$: 

![Graph of $256 \Pr[z_{252} = x]$](image)
Graph of $256 \Pr[z_{253} = x]$: 

![Graph of $256 \Pr[z_{253} = x]$](image-url)
Graph of $256 \Pr[z_{254} = x]$:
Graph of $256 \Pr[z_{255} = x]$:
Graph of $256 \Pr[z_{256} = x]$: 
2013 AlFardan–Bernstein–Paterson–Poettering–Schuldt success probability (256 trials) for recovering byte $x$ of plaintext from $2^{24}$ ciphertexts (with no prior plaintext knowledge):

Later bytes: see paper.
2013 AlFardan–Bernstein–Paterson–Poettering–Schuldt
success probability (256 trials)
for recovering byte $x$ of plaintext from $2^{25}$ ciphertexts (with no prior plaintext knowledge):

Later bytes: see paper.
2013 AlFardan–Bernstein–Paterson–Poettering–Schuldt success probability (256 trials) for recovering byte $x$ of plaintext from $2^{26}$ ciphertexts (with no prior plaintext knowledge):

Later bytes: see paper.
2013 AlFardan–Bernstein–Paterson–Poettering–Schuldt
success probability (256 trials) for recovering byte $x$ of plaintext from $2^{27}$ ciphertexts (with no prior plaintext knowledge):

Later bytes: see paper.
2013 AlFardan–Bernstein–Paterson–Poettering–Schuldt success probability (256 trials) for recovering byte $x$ of plaintext from $2^{28}$ ciphertexts (with no prior plaintext knowledge):

Later bytes: see paper.
2013 AlFardan–Bernstein–Paterson–Poettering–Schuldt
success probability (256 trials) for recovering byte $x$ of plaintext from $2^{29}$ ciphertexts (with no prior plaintext knowledge):

Later bytes: see paper.
2013 AlFardan–Bernstein–Paterson–Poettering–Schuldt success probability (256 trials) for recovering byte $x$ of plaintext from $2^{30}$ ciphertexts (with no prior plaintext knowledge):

Later bytes: see paper.
2013 AlFardan–Bernstein–Paterson–Poettering–Schuldt
success probability (256 trials)
for recovering byte $x$ of plaintext
from $2^{31}$ ciphertexts (with no prior plaintext knowledge):

Later bytes: see paper.
2013 AlFardan–Bernstein–Paterson–Poettering–Schuldt
success probability (256 trials) for recovering byte $x$ of plaintext from $2^{32}$ ciphertexts (with no prior plaintext knowledge):

Later bytes: see paper.
Why does this happen?

For years we’ve had AES; AES-GCM; defenses against various side-channel attacks.

We simply have to educate the software and hardware engineers choosing crypto primitives, right?
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Maybe, maybe not.

Does AES-GCM actually do what the users need?
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Maybe, maybe not.

Does AES-GCM actually do what the users need?

Often it doesn’t.

Most obvious issue: performance.
e.g. 2001 Rivest: “The ‘heart’ of RC4 is its exceptionally simple and extremely efficient pseudo-random generator. . . . RC4 is likely to remain the algorithm of choice for many applications and embedded systems.”

e.g. OpenSSL still uses table-based implementations of AES for speed on most CPUs, leaking many key bits; see, e.g., 2012 Weiß–Heinz–Stumpf.

e.g. RFIDs need small ciphers.
Major research direction: achieve better performance than AES-GCM\textit{without} sacrificing security.

Fit into low power (watts), low area (square micrometers), sometimes low latency (seconds); minimize area $\times$ seconds/byte; minimize energy (joules)/byte.

Many different CPUs, FPGAs, ASIC manufacturing technologies.

Many different input sizes, precomputation possibilities, etc.
Can one design do very well in hardware and software?

Some inspirational examples: Trivium and Keccak are “hardware” designs but not bad in software.
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Another approach: replace ARX with “ORX”. Skein-type mix doesn’t work but can imitate Salsa20: compose $a^\wedge=((b|c)<<r)$. Needs a few more rounds, but friendlier to hardware.
Another major research direction: achieve better security than AES-GCM without sacrificing performance.

Typical 128-bit blocks are starting to feel too small. Limit impact of collisions? Use larger blocks?
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Typical 128-bit pipe is starting to feel too small. Limit reforgeries? Use wider pipe?

Has anyone tried optimizing 192-bit/256-bit poly hashes? (We’ve started some work.)
Allow repeated message numbers?

User has to expect that encrypting \((n, m)\) and \((n, m')\) will tell attacker whether \(m = m'\).
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Is this compatible with fast forgery rejection?

One approach: build $HFFFF$ Feistel block cipher; reuse first $H$ for fast auth with repeated message numbers; reuse last $H$ for another auth with fast forgery rejection. But this consumes bandwidth.
Many more directions in authenticated ciphers.

AES-GCM is clearly not the end of the story.

Can build better modes using same MAC, cipher.

Can build better MACs, combine with same cipher.

Can build better block ciphers, stream ciphers.

Can build better integrated authenticated ciphers.
CAESAR

“Competition for Authenticated Encryption: Security, Applicability, and Robustness”

competitions.cr.yp.to

Mailing list: crypto-competitions+subscribe@googlegroups.com

NIST is much too busy to run another competition but has generously provided a $333099 “Cryptographic competitions” grant to UIC.