High Availability in the Internal Google Key Management System (KMS)

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Google LLC

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Not the Google Cloud KMS
Google’s key hierarchy

**Storage Systems (Millions)**
- Data encrypted with DEKs, DEKs are encrypted with KEKs

**KMS (Tens of Thousands)**
- KEKs are stored in KMS

**Root KMS (Hundreds)**
- KMS is protected with a KMS master key in Root KMS

**Root KMS master key distributor (Hundreds)**
- Root KMS master key is distributed in memory

**Physical safes (a few)**
- Root KMS master key is backed up on hardware devices
Why use a KMS?

Core motivation: code needs secrets!

Where:
● In code repository?
● On production hard drives?

Alternative:
● Use a KMS!
Centralized Key Management

Solves key problems for everybody:

- Access control: who <humans or services?>, what <is the build verifiable?>
- Auditing of cryptographic operations
- Key-handling code management
- Separation of trust
What could go wrong?
The Great Gmail Outage of 2014

https://googleblog.blogspot.com/2014/01/todays-outage-for-several-google.html
Each team maintains their own KMS configurations, all stored in Google’s monolithic repo. 

Normal Operation

- Individual Team Config Changes
- Sees incorrect image of source repo

Normal Operation

- Merging Problem
- Truncated Config

Normal Operation

- Update Data Pusher
- All Local Configs
- KMS Servers
- Many KMS Servers
- Local Config
- KMS
- Client

Normal Operation

- A bad config pushed globally means a global outage
- Incorrect image of source repo

Normal Operation

- Each config is pushed to all KMS servers
- All KMS servers see a global config file

Normal Operation

Which get automatically merged into a combined config file
Which is distributed to all KMS shards for serving
Lessons Learned

The KMS had become

- a single point of failure
- a startup dependency for services
- often a runtime dependency

==> KMS Must Not Fail Globally
KMS Must Not Fail Globally

- Eliminated the global control plane
- Controlled rollout of binaries and configuration
- Minimize dependencies
- Regional failure isolation
- … for the KMS and all dependencies
## Google KMS - (some) Requirements

<table>
<thead>
<tr>
<th>Category</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>&gt; 99.9995% of requests are served</td>
</tr>
<tr>
<td>Latency</td>
<td>99% of requests are served &lt; 10 ms</td>
</tr>
<tr>
<td>Scalability</td>
<td>All of Google’s Key Management needs</td>
</tr>
<tr>
<td>Security</td>
<td>Effortless &amp; foolproof Key Rotation</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Requests/Core: As high as possible</td>
</tr>
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</table>
Design Choices

- Granularity of Encryption
- Rate of Change
- Position in the trust/key hierarchy
Stateless Serving

Insight: At the KMS layer, key material is not mutable state.

Immutable Key material + Key Wrapping
    ==> Stateless Server ==> Trivial Scaling

Keys in RAM ==> Low Latency Serving
Google KMS - What we ended up with

- Infrastructure for managing secrets
- Wraps/unwraps data-encryption-keys (DEK) using keys that never leave the service (KEK)
- Not a traditional database/storage system
- Not a data-encryption service
# Google KMS - Requirements Met

<table>
<thead>
<tr>
<th>Category</th>
<th>Requirement</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>&gt; 99.9995% of requests are served</td>
<td>No downtime since the Gmail outage in 2014 January</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;&gt; 99.9999%</td>
</tr>
<tr>
<td>Latency</td>
<td>99% of requests are served &lt; 10 ms</td>
<td>99.9% of requests are served &lt; 200 μs</td>
</tr>
<tr>
<td>Scalability</td>
<td>All of Google’s Key Management needs</td>
<td>~10^7 requests/sec</td>
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<tr>
<td></td>
<td></td>
<td>~10^4 processes &amp; cores</td>
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<tr>
<td>Efficiency</td>
<td>Requests/Core: As high as possible</td>
<td>4-12K requests/sec/core</td>
</tr>
</tbody>
</table>
Why rotate keys?

● Key Compromise
  ○ *Also requires access to cipher text*

● Broken Ciphers
  ○ *Access to cipher text is enough*

● Rotating keys limits the window of vulnerability

● *But* Rotating Keys is error prone  =>  data loss
Robust Key Rotation at Scale - 0

Goals

1. KMS clients design with rotation in mind
2. Using multiple key versions is no harder than using a single key
3. Very hard to lose data
Robust Key Rotation at Scale - 1

- Clients choose
  - Frequency of rotation: e.g. every 30 days
  - TTL of cipher text: e.g. 30, 90, 180 days, 2 years, etc.

- KMS guarantees ‘Safety Condition’
  - All ciphertext produced within the TTL can be deciphered using a keyset in the KMS.

- Tightly integrated with Google's standard cryptographic library
  - Supports **multiple key versions**
  - Each of which can be a different cipher
Robust Key Rotation at Scale - 2

- **KMS**
  - Derives the number of key versions to retain
  - Adds/Promotes/Demotes/Deletes Key Versions over time
  - Generation/Deletion of key versions completely separate from serving system
  - Rolled out slowly

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<th>T0</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
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<th>T8</th>
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</thead>
<tbody>
<tr>
<td><strong>K1</strong></td>
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<td>P</td>
<td>P</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>SFR</td>
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<td>P</td>
<td>P</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>SFR</td>
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<tr>
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<td>P</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>SFR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>K4</strong></td>
<td>A</td>
<td>P</td>
<td>P</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
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*Time →*

**A** - Active

**P** - Primary

**SFR** - Scheduled for Revocation
Mitigating Hardware Faults

○ Crypto provides leverage and can amplify errors -
  ■ A single undetected bit error in a wrapping of a DEK can render large chunks of data unusable.

○ Causes of bit errors
  ■ NICs twiddle bits, Broken CPUs, Cosmic rays flip bits in DRAM.

○ Software Mitigations
  ■ Verify correctness of crypto ops at process start
  ■ After wrapping DEKs and before responding, we Unwrap
  ■ Storage services
    ● Read back plain text after writing encrypted data blocks
    ● Replicate/parity protect at a higher layer
Google KMS - Summary

Implementing encryption at scale required highly available key management.

At Google’s scale this meant 6.5 9s of availability.

To achieve HA and security requirements, we used several strategies:

- Best practices for change management and staged rollouts
- Minimized dependencies and aggressively defend against their unavailability
- Isolated by region & client type
- Combined immutable keys + wrapping to achieve scale
- A declarative API for key rotation
- Defend against hardware issues
Thank You!
Merci! Danke! Grazie!
Further Reading

- Google Cloud Encryption at Rest whitepaper: https://cloud.google.com/security/encryption-at-rest/default-encryption/
- CrunchyCrypt cryptography and key versioning library: https://github.com/google/crunchy
The End