



CRASH-WORTHY
TRUSTWORTHY
SYSTEMS
RESEARCH AND
DEVELOPMENT

Security-Oriented Analysis of Application Programs (SOAAP)

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SRI International
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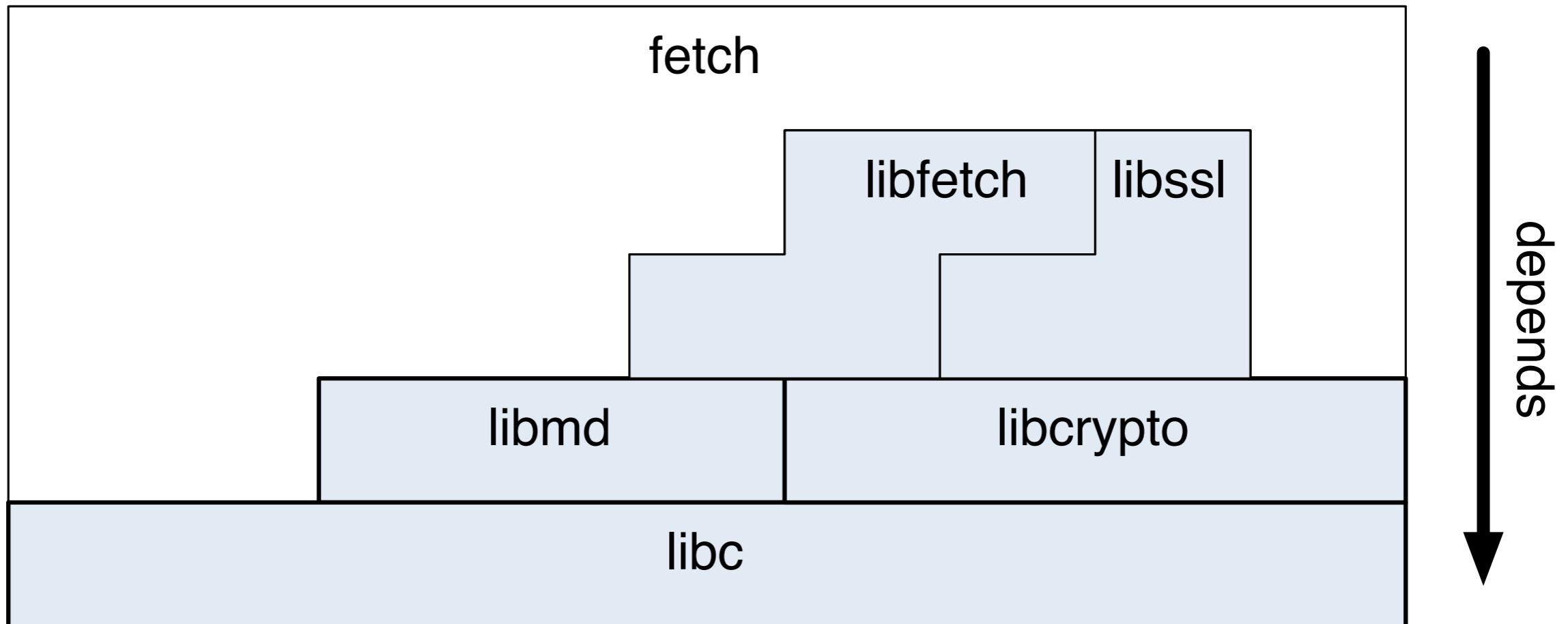


The Enemy ®

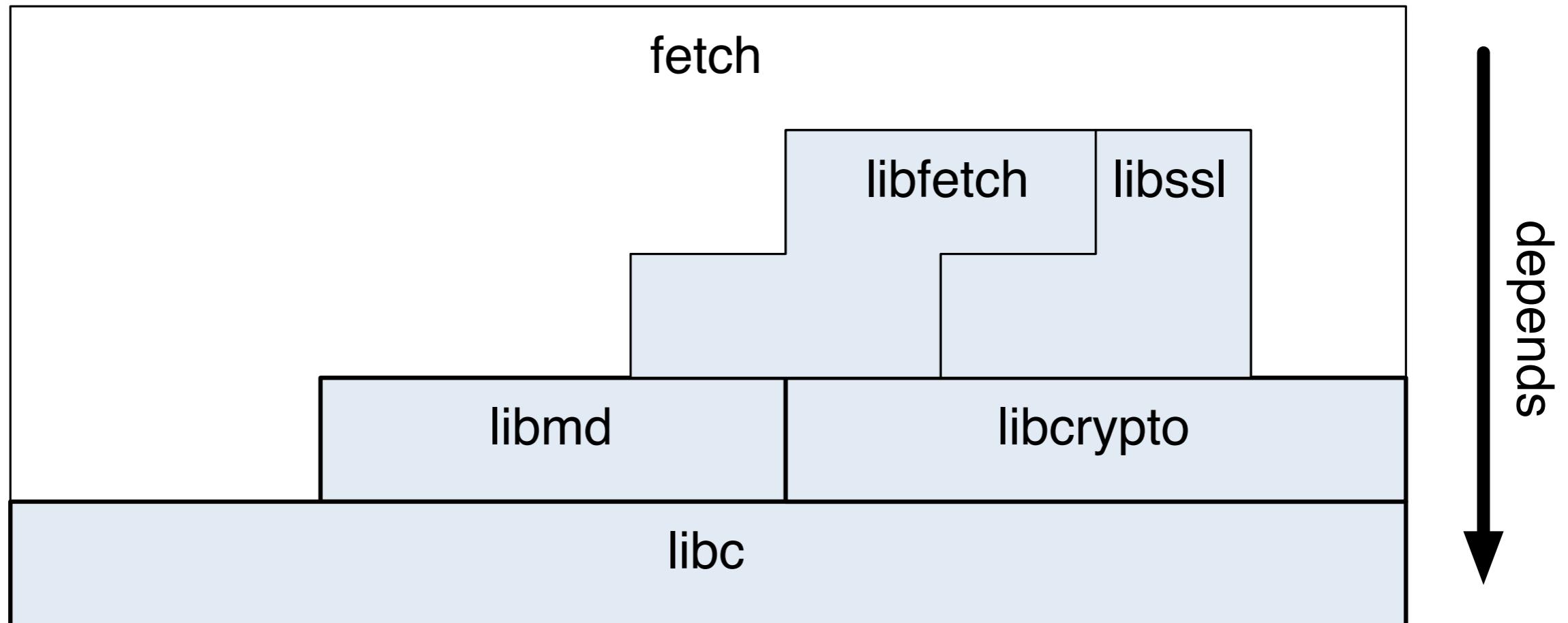
- Today's adversary is very sophisticated and able to execute arbitrary code through many means
- It's not just about buffer overflows any more
- Software stack comprises components from numerous **untrusted** origins. How do we know they do not contain **trojans** or **backdoors**?



The Battlefield ®



The Battlefield ®



We need mitigation techniques that can work for
both **known** and **unknown** vulnerabilities

Principle of least privilege

[Saltzer and Schroeder, 1975]

- Traditionally, UNIX processes run with the ambient rights of the user executing them
- An exploited vulnerability leaks all ambient rights
- But capturing policy for required rights is very difficult



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Solution: minimise the amount of code that runs with elevated privileges (TCB) and execute the rest in least privileged sandboxes with limited rights:
E.g. “only read file X and write file Y”

- But capturing policy for required rights is very difficult



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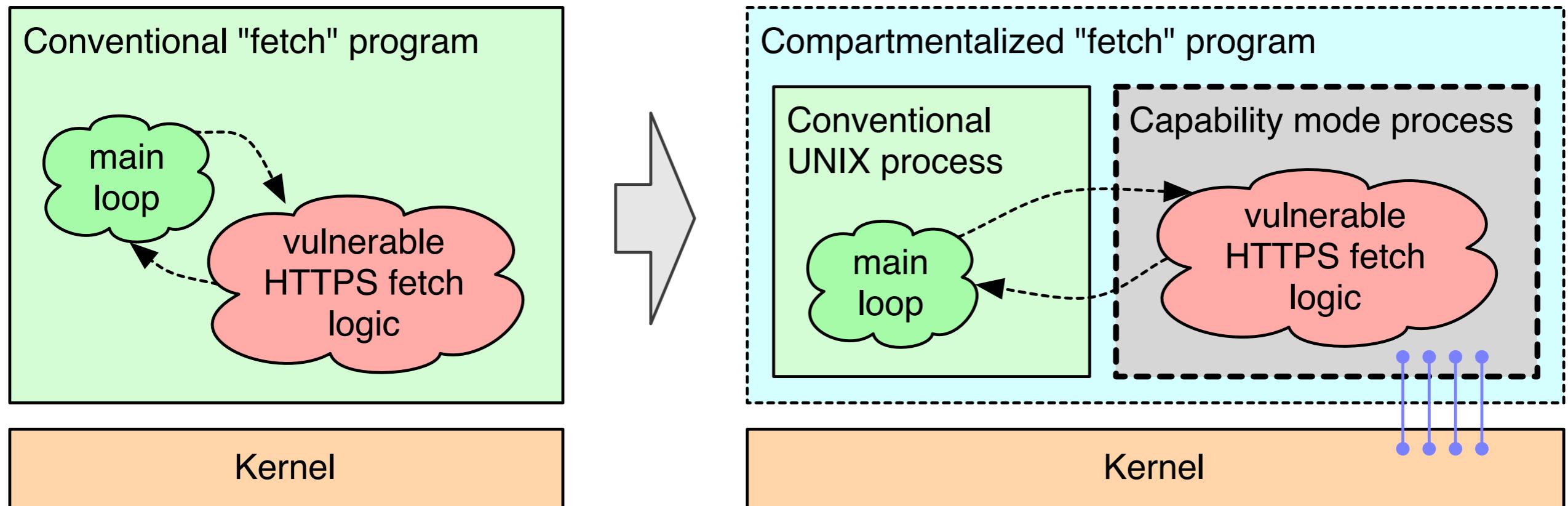
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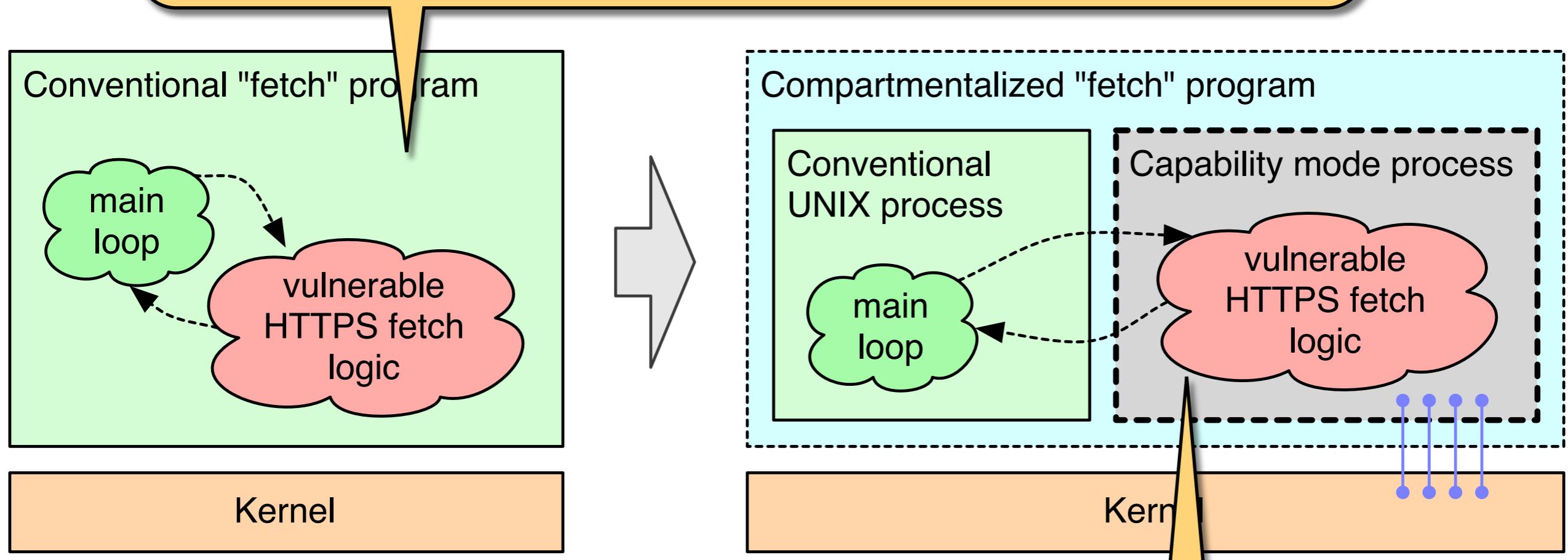


Software compartmentalisation



- Software compartmentalisation decomposes applications into many isolated components
- Each runs with only the rights required to perform its function

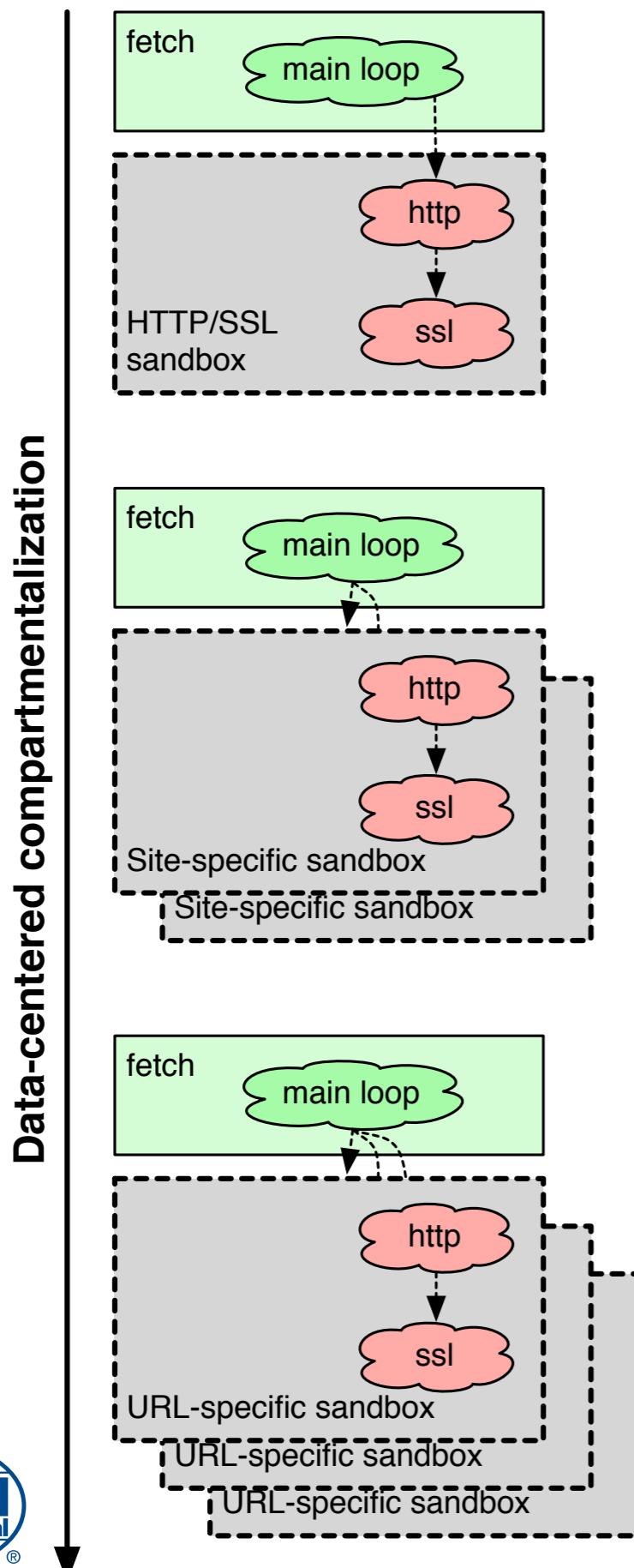
When a conventional application is compromised, its ambient rights are leaked to the attacker, e.g., full network and file system access.



When a compartmentalised application is compromised, only rights held by the exploited component leak to the attacker.

Most vulnerabilities will no longer yield significant rights, and attackers must exploit many vulnerabilities to meet their goals.

Code-centred compartmentalization



- Applications can be compartmentalized in many different ways, trading off **security**, **performance** and **complexity**.
- Finer-grained decompositions **mitigate** vulnerabilities better, as attacks yield fewer rights.
- The combination of code-centered and data-centered compartmentalisations aligns with the **object-capability** model



Lessons from Capsicum

- Multi-year Cambridge/Google research project into the structure of operating system security (Watson, Anderson, Laurie, Kennaway)
- **Capsicum**: new operating system primitives for application compartmentalisation, reference application suite including Chromium





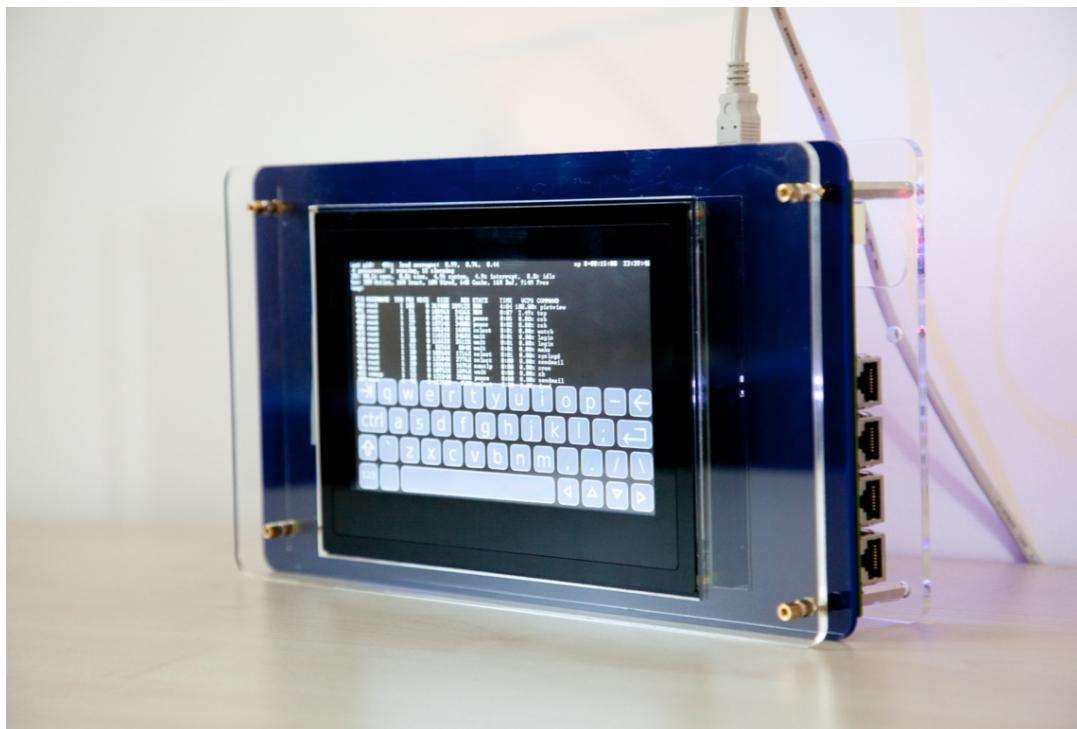
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Lesson: software designs that employ the principle of least privilege are neither **easily** nor **efficiently** represented in current hardware



Capability Hardware Enhanced RISC Instructions (CHERI)



- Joint SRI/Cambridge project
- **Modify hardware platform to enforce program protection**
- Capability registers, tagged memory
- Replace context switches with hardware message passing within an address space
- Apply RISC design philosophy: minimal, compiler-friendly hardware support to provide efficient protection

Compartmentalisation is hard!

- Compartmentalisation turns a “local” program into a distributed one
- Have to preserve functional correctness
 - e.g. data synchronisation/consistency
- Many different compartmentalisations present trade-offs: **performance, security** and **complexity**
- Have to find a mapping from intended goals to the underlying sandboxing technology

Gzip

- Compartmentalisation helps to mitigate vulnerabilities:

“The gzip program contains a stack modification vulnerability that may allow an attacker to execute arbitrary code, or create a denial-of-service condition...”

[Source: <http://www.kb.cert.org/vuls/id/381508>]

Gzip

- But getting it right is difficult, even for simple programs!

*“In adapting gzip, we were initially surprised to see a performance improvement; investigation of this unlikely result revealed that we had **failed to propagate the compression level** (a global variable) into the sandbox, leading to the incorrect algorithm selection.”*

[Watson et al. “Capsicum: practical capabilities for UNIX,” USENIX Security 2010]



Sandboxing platforms:

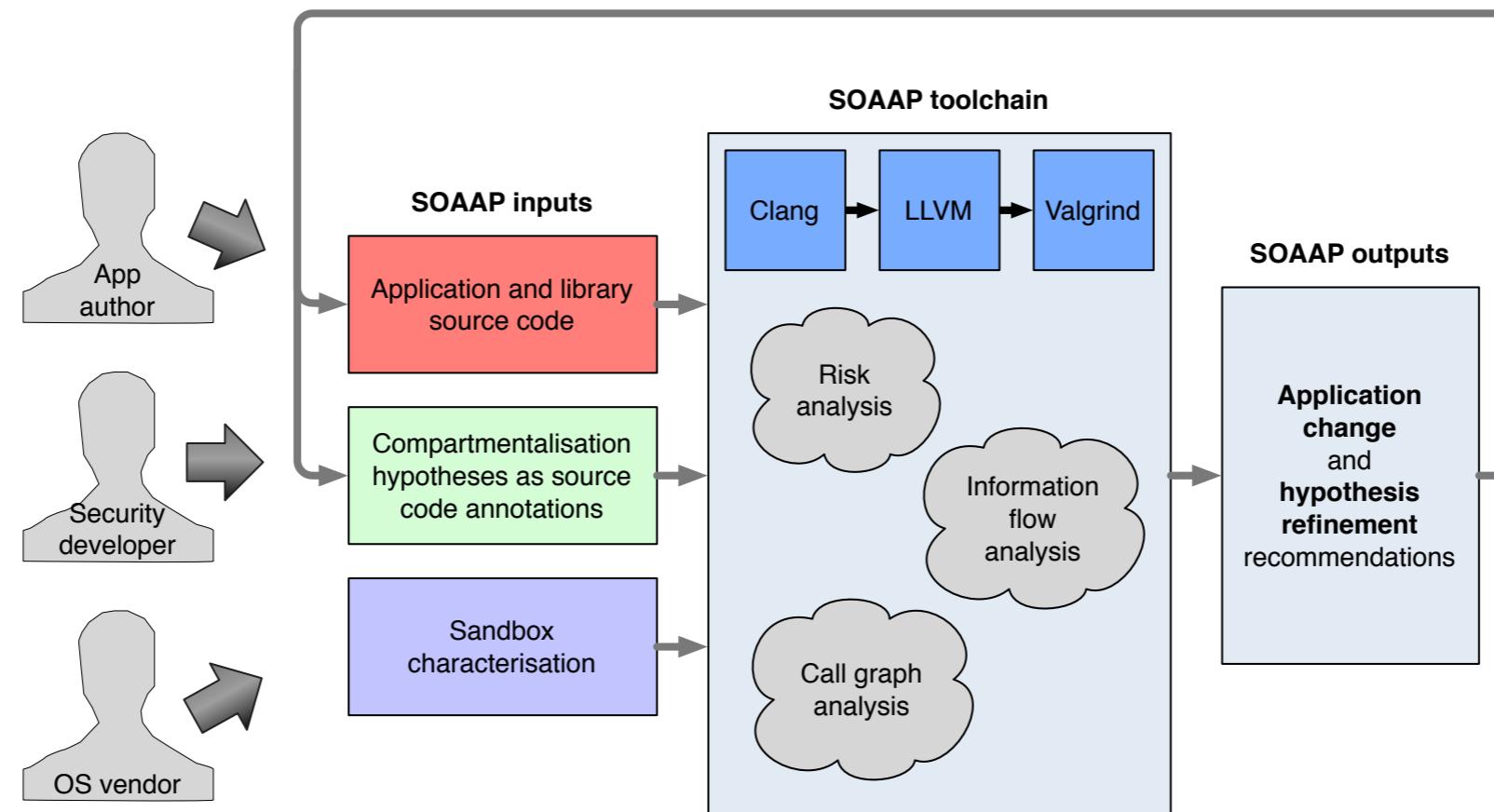
Chromium

	OS	Sandbox	LoC	FS	IPC	NET	S≠S'	Priv
DAC	Windows	DAC ACLs	22,350	⚠️	⚠️	✗	✗	✓
	Linux	chroot()	600	✓	✗	✗	✓	✗
MAC	Mac OS X	Sandbox	560	✓	⚠️	✓	✓	✓
	Linux	SELinux	200	✓	⚠️	✓	✗	✗
Cap	Linux	seccomp	11,300	⚠️	✓	✓	✓	✓
	FreeBSD	Capsicum	100	✓	✓	✓	✓	✓



Security-oriented analysis of application programs (SOAAP)

Repeated SOAAP iteration as program and hypotheses are refined



- Motivated by the programmability problem in application compartmentalisation
- Allow application programmers to easily evaluate trade-offs through semi-automated analysis of possible compartmentalisations
- Annotation-driven static and dynamic program analysis and refinement of source code – and eventually program transformation

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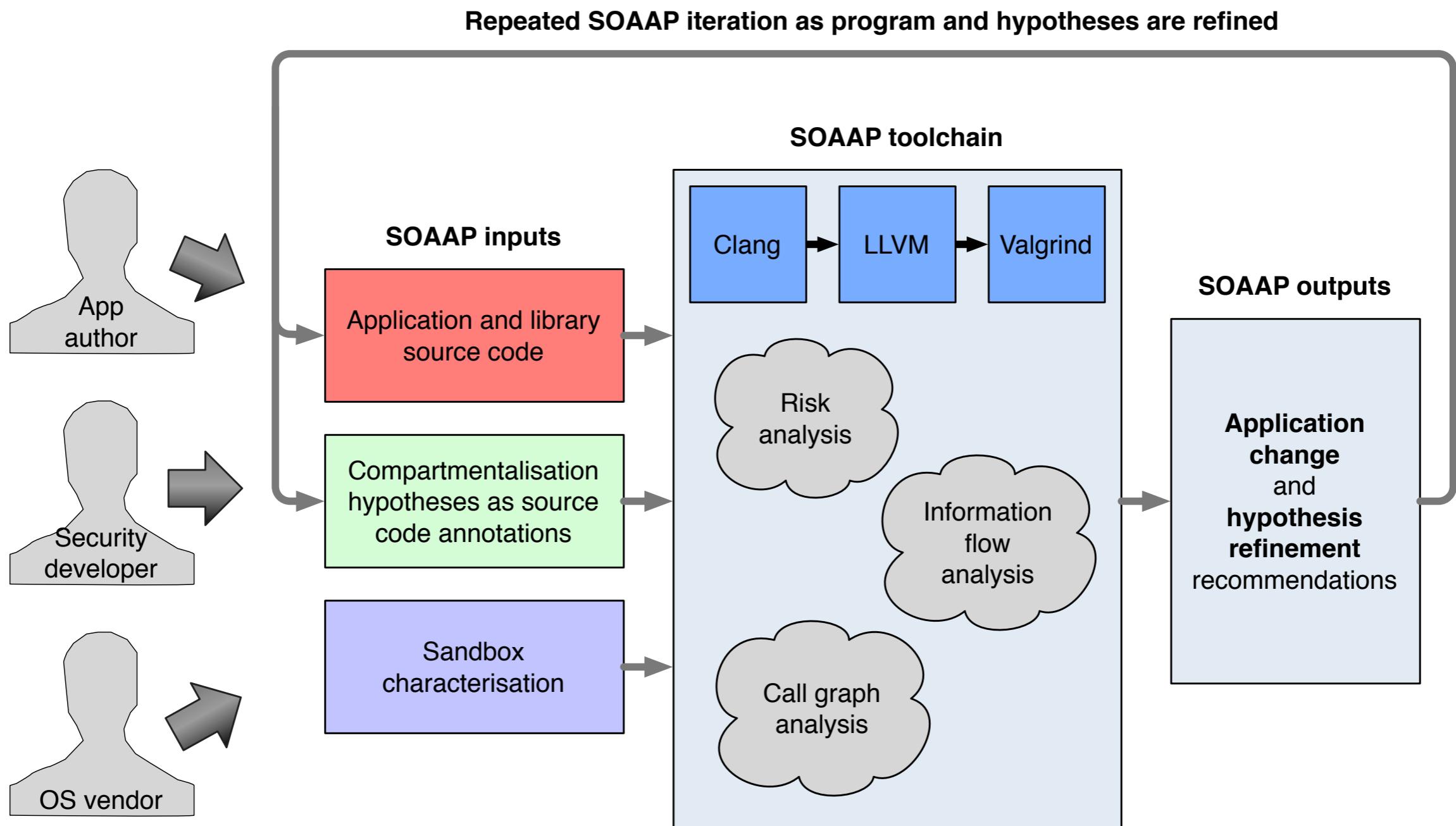
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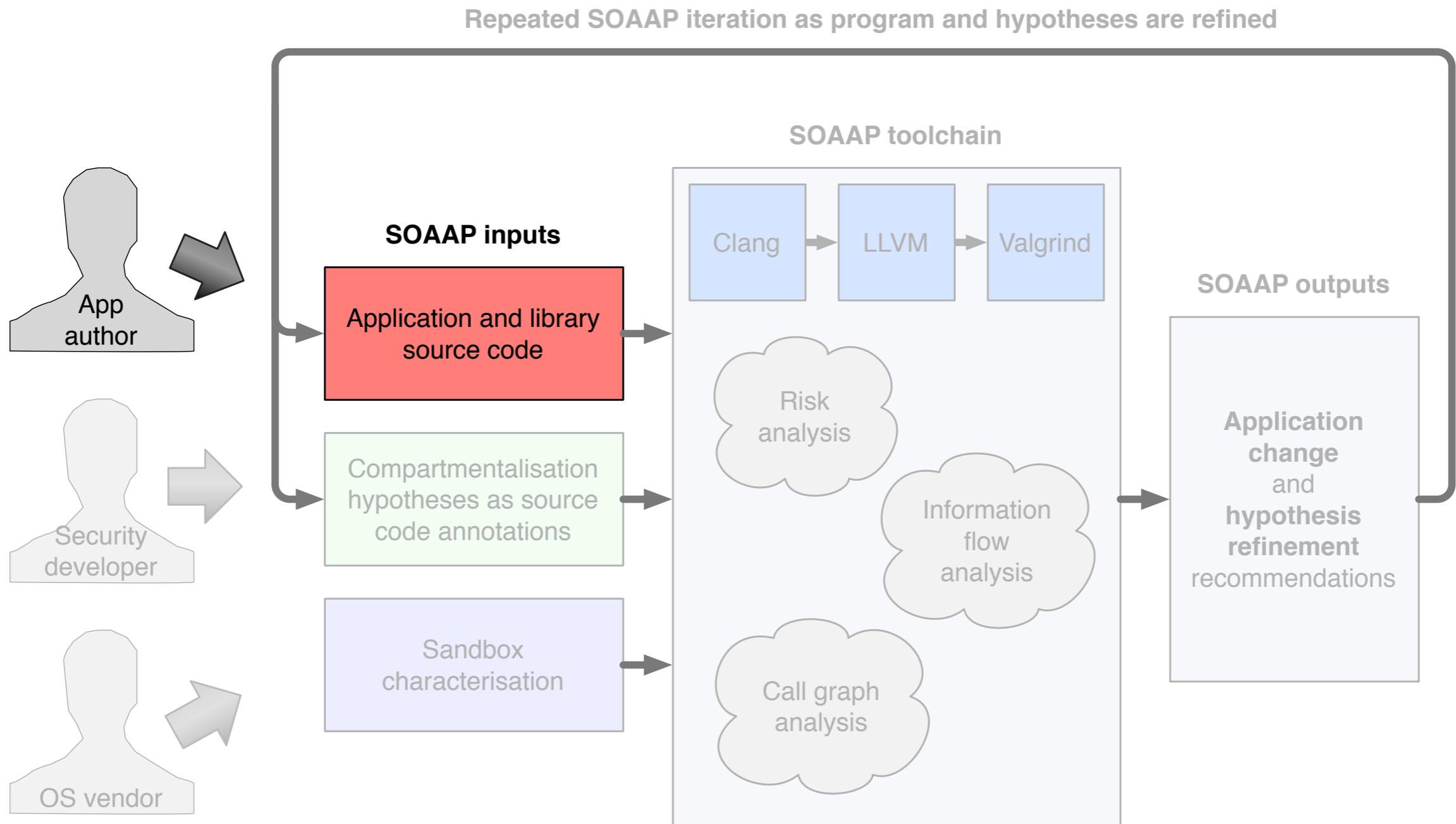
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- SOAAP analyses this **hypothesis** and gives feedback



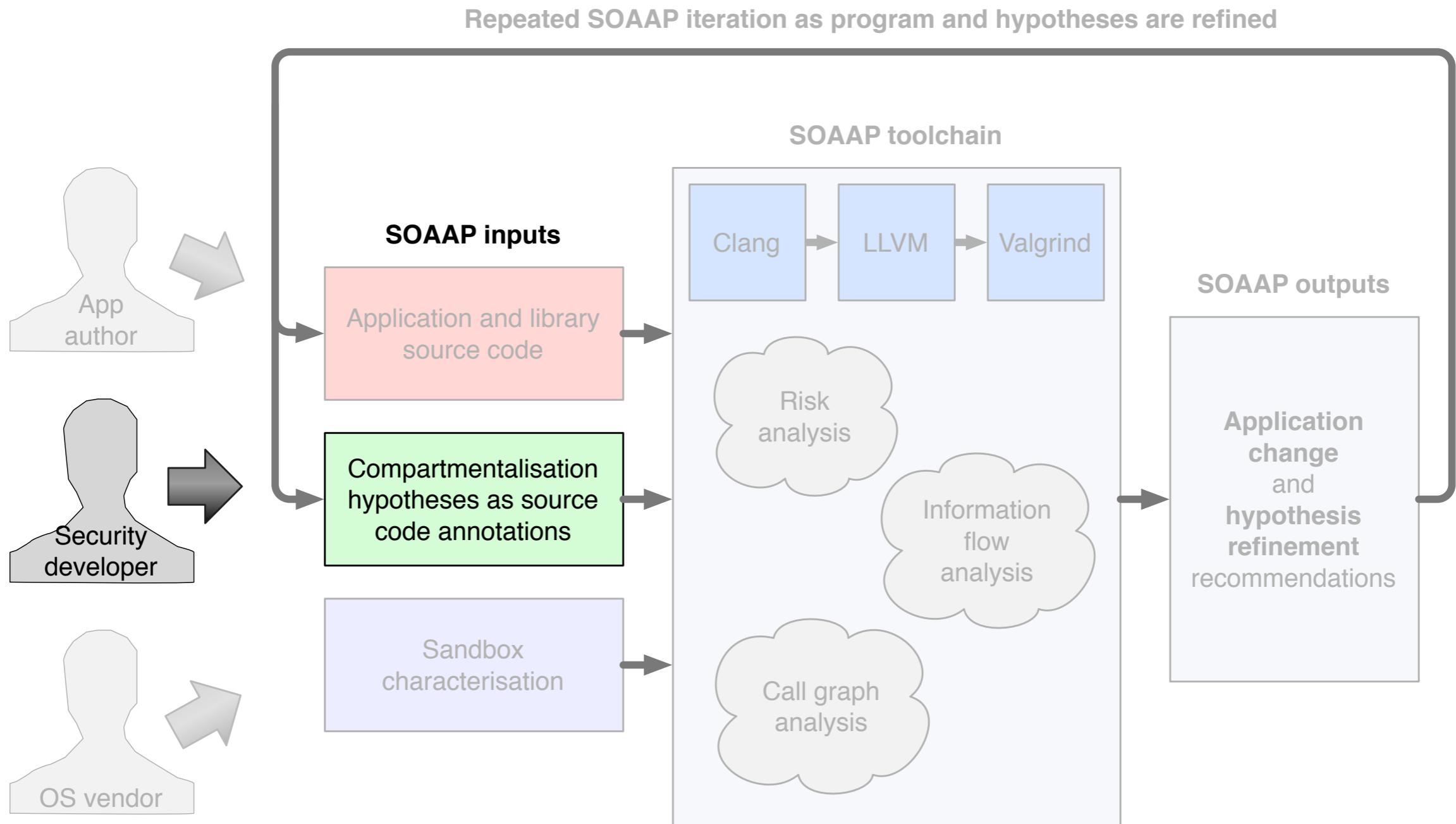
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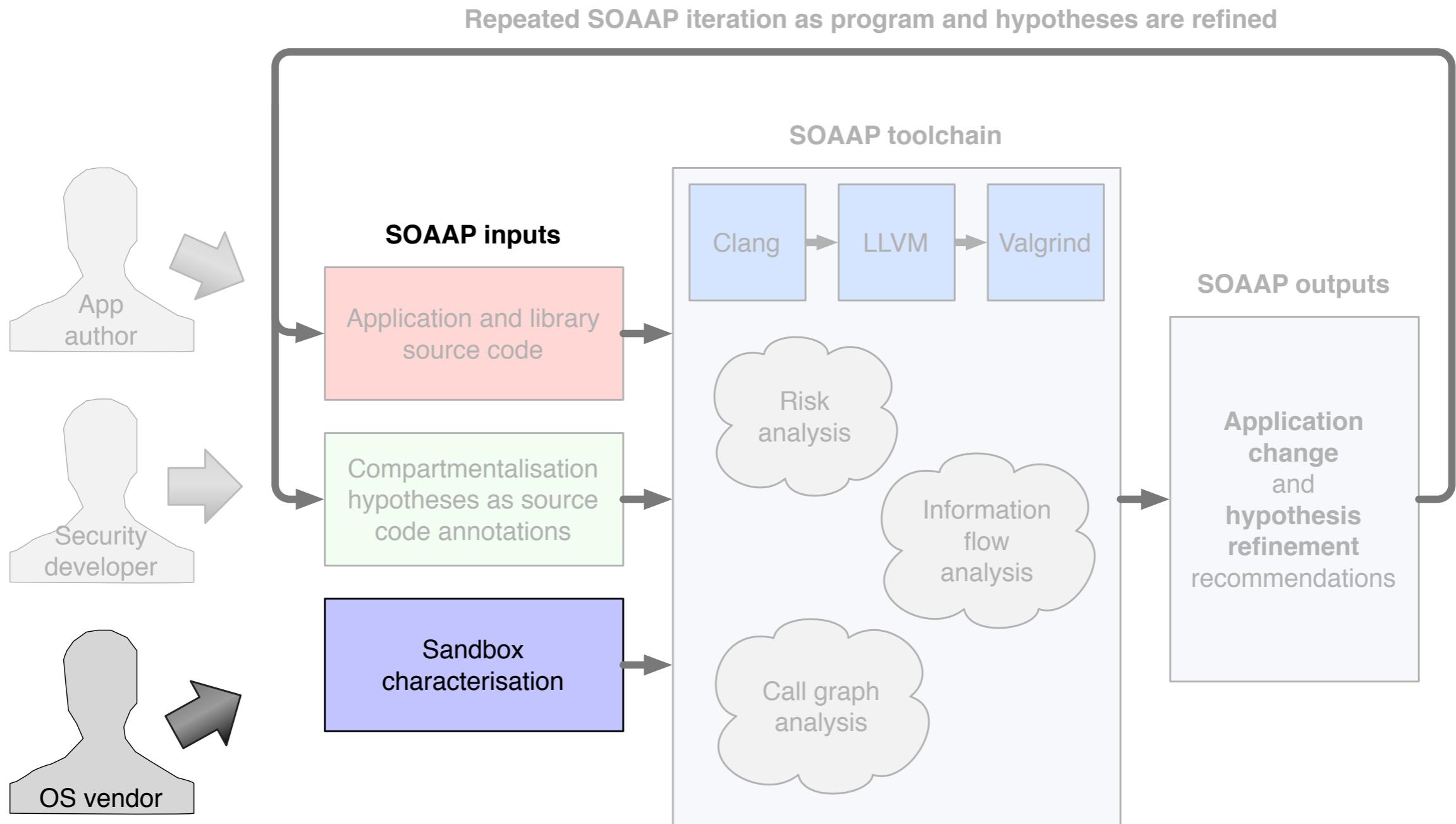
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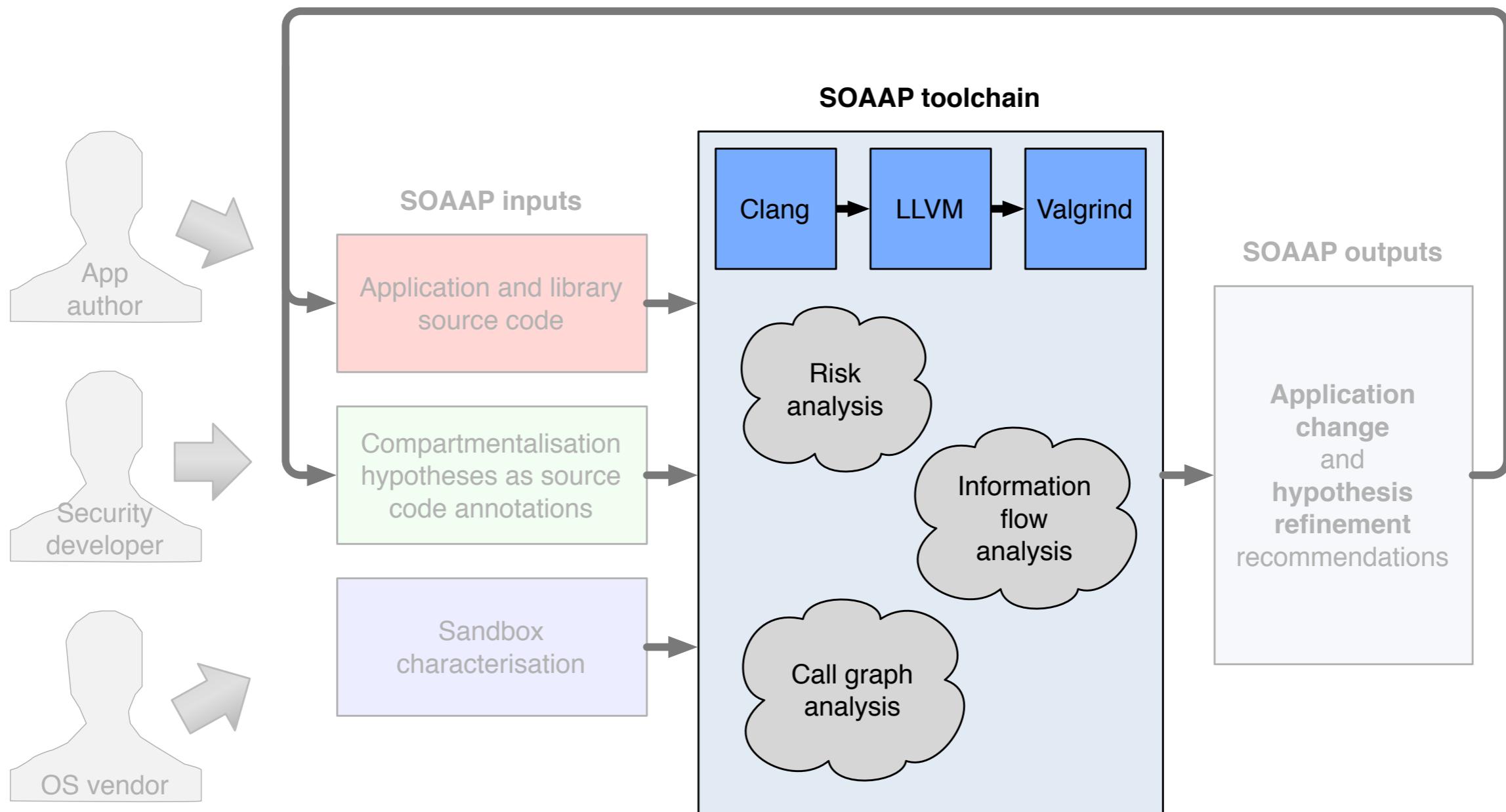


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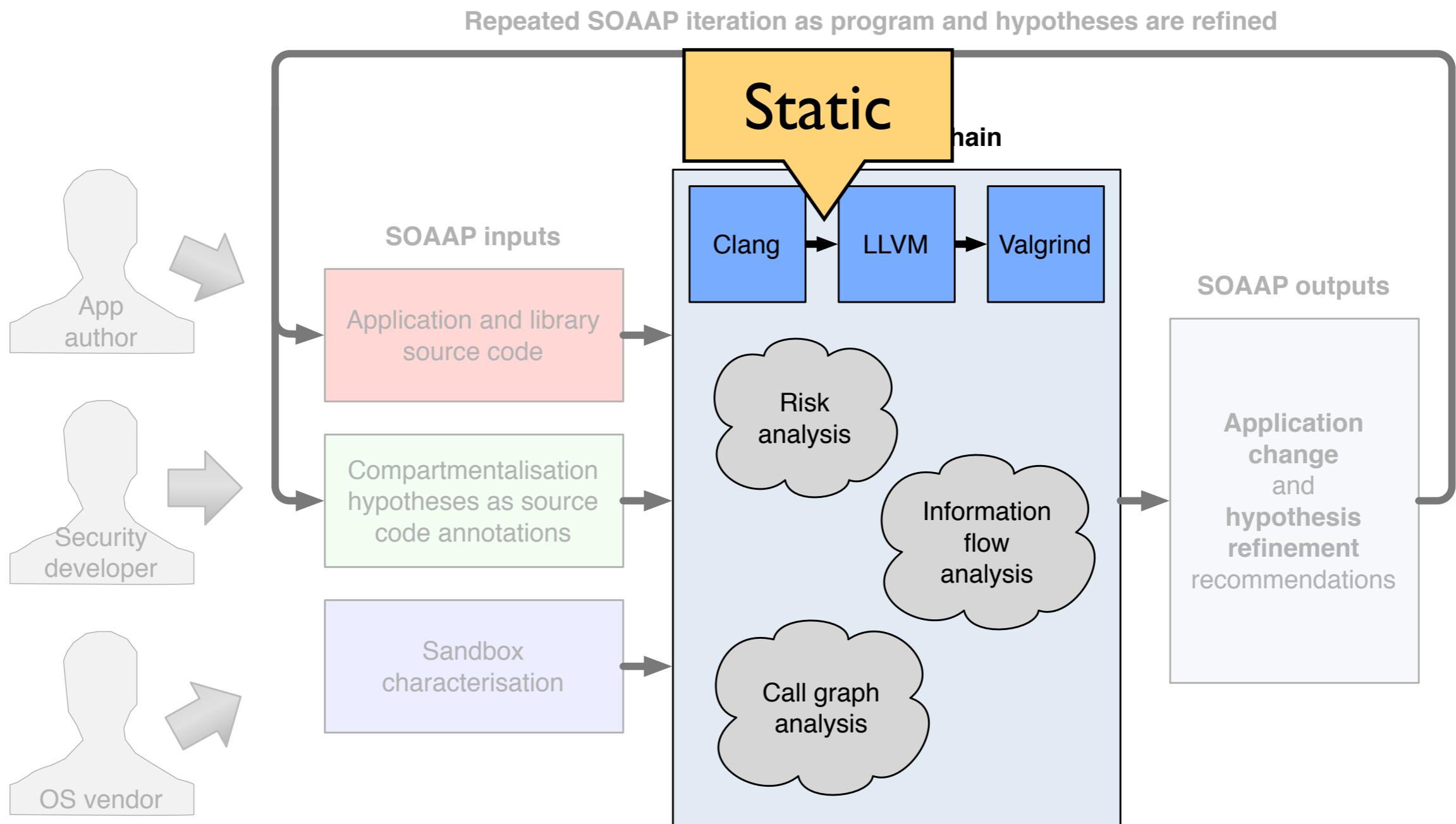


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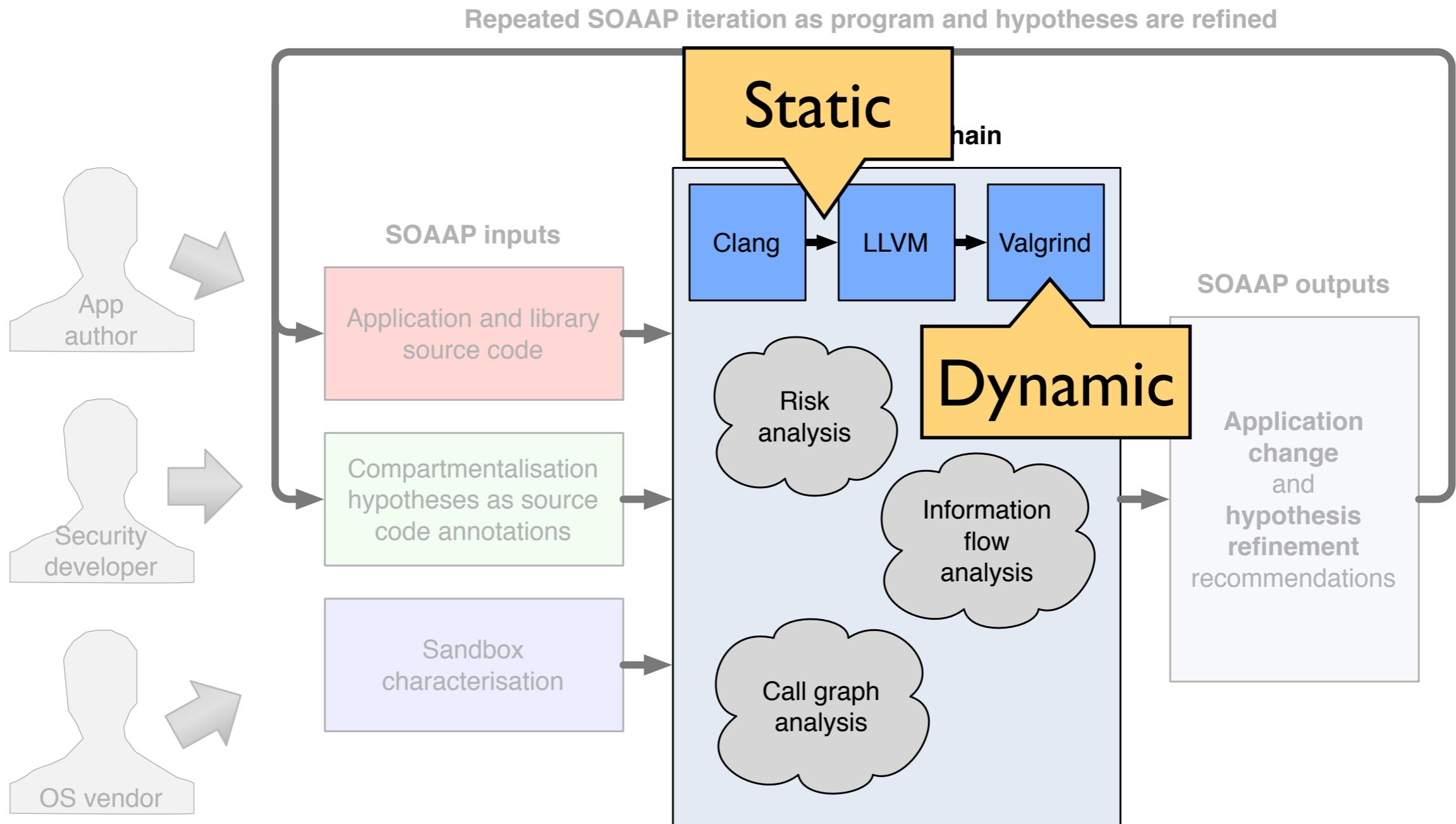
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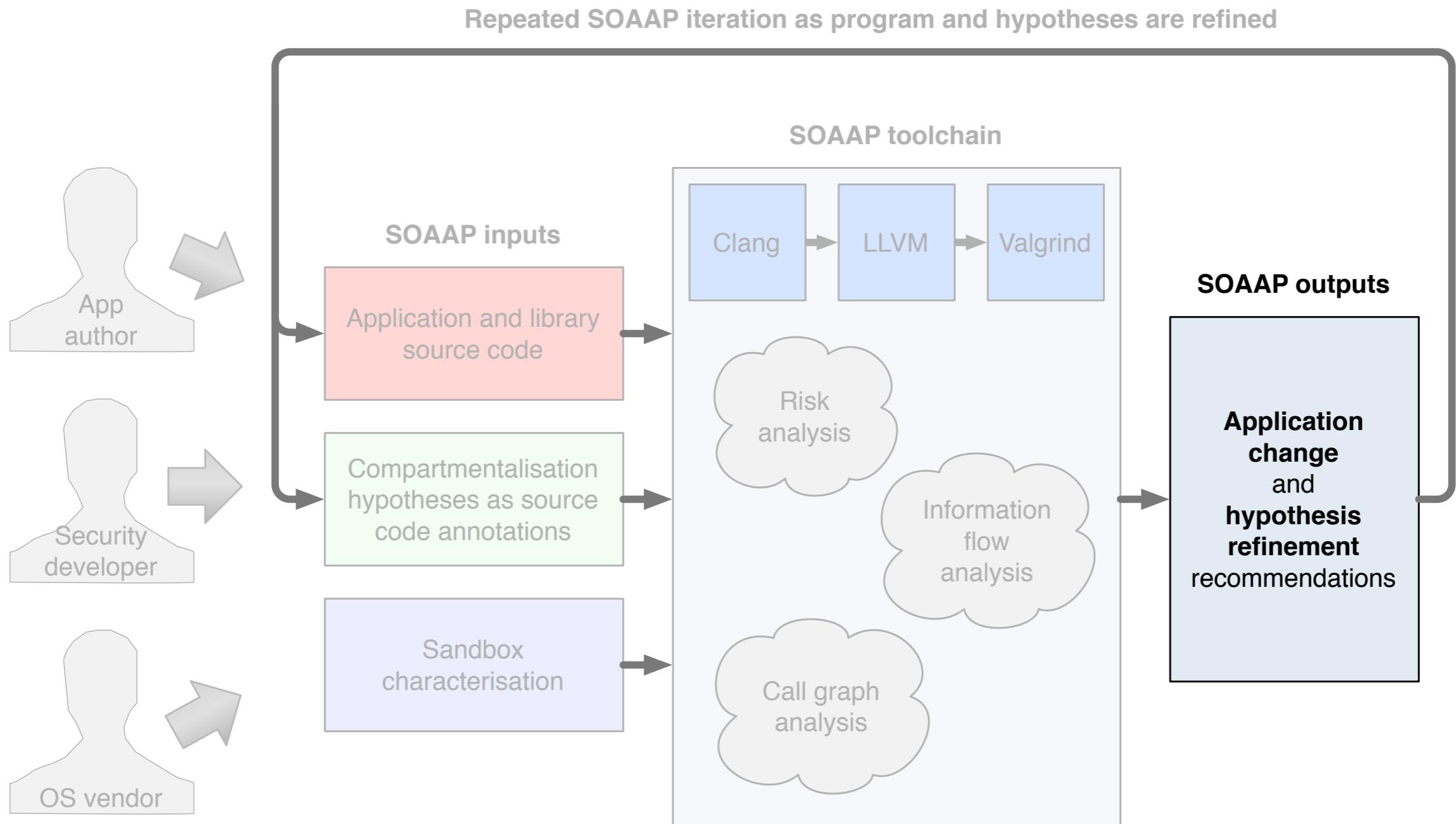
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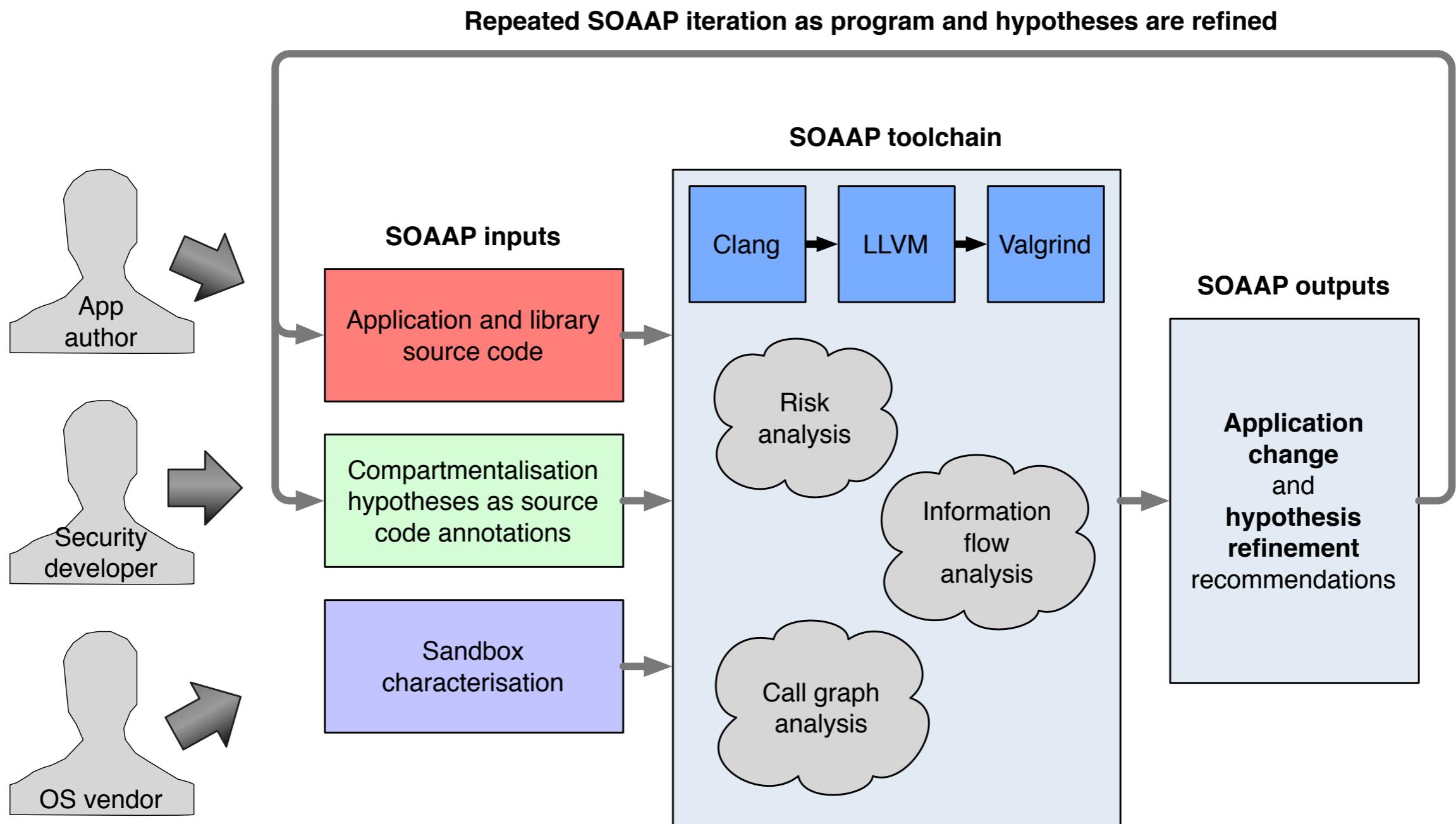
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Example

- Let's compartmentalise FreeBSD's gzip
- As a first pass, hypothetically sandbox the `gz_compress()` function
- Compile with our modified Clang/LLVM and run with our modified Valgrind

Example

```
543 /* compress input to output. Return bytes read, -1 on error */
544 __sandbox_persistent
545 static off_t
546 gz_compress(int in, int out, off_t *gsizep, const char *origname, uint32_t mtime)
547 {
548     z_stream z;
549     char *outbufp, *inbufp;
550     off_t in_tot = 0, out_tot = 0;
551     ssize_t in_size.
```

Example

“What would happen if I were to sandbox
gz_compress()?”

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547 {
548     z_stream z;
549     char *outbufp, *inbufp;
550     off_t in_tot = 0, out_tot = 0;
551     ccsize + in_size.
```

Assumption: sandboxes are forked at the start of main()



Example

```
valgrind --tool=soaap gzip -9 test.txt
```



Example

Sandbox read global variable "numflag" in method `gz_compress`, but it is not allowed to.

```
==9336==    at 0x804C27D: gz_compress (gzip.c:581)
==9336==    by 0x804B5D6: handle_file (gzip.c:1283)
==9336==    by 0x804A279: main (gzip.c:1817)
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Unspecified global variable access
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Stack trace so programmer can pinpoint



Example

```
181 static int arflag;           /* decompress mode */
182 static int lflag;            /* list mode */
183 static int __var_read numflag = 6; /* gzip -1..-9 value */
184
185 #include <mail.h>
```



Example

Annotate **numflag** as
readable from sandboxes

```
181 static int aflag;           /* decompress mode */
182 static int lflag;           /* list mode */
183 static int __var_read numflag = 6;    /* gzip -1..-9 value */
184
185 #endif CMAIL
```

Example

Global variable "numflag" is being written to in method main after a sandbox has been created and so the sandbox will not see this new value.

`==938|== at 0x8049F83: main (gzip.c:329)`

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Write to global variable outside the sandbox will not be propagated

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324     while ((ch = getopt_long(argc, argv, OPT_LIST, longopts, NULL)) != -1) {  
325         switch (ch) {  
326             case '1': case '2': case '3':  
327             case '4': case '5': case '6':  
328             case '7': case '8': case '9':  
329                 numflag = ch - '0';  
330                 break;  
331         }  
332     }  
333 }
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Write to numflag



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Example

Sandbox read from /usr/home/khilan/nfs/bsd_src/usr.bin/gzip/test.txt (fd: 3) in method __sys_read, but it is not allowed to.

```
==9381==    at 0x172D03: __sys_read (in /lib/libc.so.7)
==9381==    by 0x804B5E6: handle_file (gzip.c:1283)
==9381==    by 0x804A289: main (gzip.c:1817)
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Sandbox wrote to /usr/home/khilan/nfs/bsd_src/usr.bin/gzip/test.txt.gz (fd: 4) in method __sys_write, but it is not allowed to.

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==9381==    at 0x172CE3: __sys_write (in /lib/libc.so.7)
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Unspecified file write

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“Can read from
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“Can write to file descriptor **out**”

We are effectively annotating the program to use Capsicum: sandboxes, delegated rights, call gates, etc.



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	Linux	SELinux	200	✓	⚠️	✓	✗	✗
Cap	Linux	seccomp	11,300	⚠️	✓	✓	✓	✓
	FreeBSD	Capsicum	100	✓	✓	✓	✓	✓

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 - Modulo different sandboxing technologies (e.g. Capsicum, seccomp, SELinux, chroot/setuid).
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- Trade-off exploration
- Can also validate the correctness/security of already compartmentalised programs

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- SOAAP also provides annotations allowing declaring code that is deemed risky:
 - Due to past vulnerabilities:
past_vulnerability
 - Due to heuristics (plan to automate this):
vulnerable

OpenSSH Example

```
20 __past_vulnerability
21 ⊕ static void
22 input_userauth_info_response(int type, u_int32_t seq, void *ctxt)
23 {
24     Authctxt *authctxt = ctxt;
25     KbdintAuthctxt *kbdintctxt;
26     int i;
27     u_int nresp;
28     char **response = NULL;
29
30     // ... other code here ...
31
32     nresp = packet_get_int();
33     if (nresp > 100)
34         fatal("input_userauth_info_response: nresp too big %u", nresp);
35     if (nresp > 0) {
36         response = xmalloc(nresp * sizeof(char *));
37         for (i = 0; i < nresp; i++)
38             response[i] = packet_get_string(NULL);
39     }
40     packet_check_eom();
41 }
```



OpenSSH Example

“This method is known to have previously had a vulnerability”

```
20 __past_vulnerability
21 static void
22 input_userauth_info_response(int type, u_int32_t seq, void *ctxt)
23 {
24     Authctxt *authctxt = ctxt;
25     KbdintAuthctxt *kbdintctxt;
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35     if (nresp > 0) {
36         response = xmalloc(nresp * sizeof(char *));
37         for (i = 0; i < nresp; i++)
38             response[i] = packet_get_string(NULL);
39     }
40     packet_check_eom();
41 }
```



Future plans

- **Confidentiality** - employ information flow analyses to validate flows for sensitive data
- **Risk** - automate the classification of risky code, e.g. machine learning, fuzzbuster
- **Sandbox characterisations**
- Apply SOAAP annotations to already-compartmentalised software

Proposed Evaluation

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- Are new bugs found in previously compartmentalised programs, illustrating the benefits of this approach?

Proposed Evaluation

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- Do performance predictions made by SOAAP prove accurate?
- Can we scale up SOAAP-based exploration to both very large collections of programs, such as the footprint of a complete UNIX system, or individually large (monolithic) applications such as web browsers and mail clients?

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- This work was sponsored by DARPA and Google
- Builds on taintgrind tool by Wei Ming Khoo
 - Originally designed for malware analysis...



Closing remarks

- Goal is to release the SOAAP tools as open source. Build instructions can be found here:
<http://www.cl.cam.ac.uk/research/security/ctsrdf/soaap.html>
- Talk was well received at the recent FreeBSD developer summit, AHANS 2012 workshop and LLVM day
 - Lots of interest from Capsicum developers
 - Already downloading and using SOAAP

