NICTA

Proof Engineering Considered Essential

FM'14 Singapore

Gerwin Klein

Australian Government
Department of Broadband, Communications and the Digital Economy
Australian Research Council

NICTA Funding and Supporting Members and Partners
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Windows

An exception 06 has occured at 0028:C11B3ADC in VxD DiskTSD(03) +
00001660. This was called from 0028:C11B40C8 in VxD voltrack(04) +
00000000. It may be possible to continue normally.

* Press any key to attempt to continue.
* Press CTRL+ALT+RESET to restart your computer. You will
   lose any unsaved information in all applications.

Press any key to continue

A problem has been detected and windows has been shut down to prevent damage
to your computer.

A process or thread crucial to system operation has unexpectedly exited or been
terminated.

If this is the first time you've seen this Stop error screen,
restart your computer. If this screen appears again, follow
these steps:

Check to make sure any new hardware or software is properly installed.
If this is a new installation, ask your hardware or software manufacturer
for any windows updates you might need.

If problems continue, disable or remove any newly installed hardware
or software. Disable BIOS memory options such as caching or shadowing.
If you need to use Safe Mode to remove or disable components, restart
your computer, press F8 to select Advanced startup options, and then
select Safe Mode.

Technical information:

*** STOP: 0x000000F4 (0x00000003,0x85866DA0,0x85866F14,0x805CBCA8)


the Bay
the Bay

Isolation

Isolation is the Key

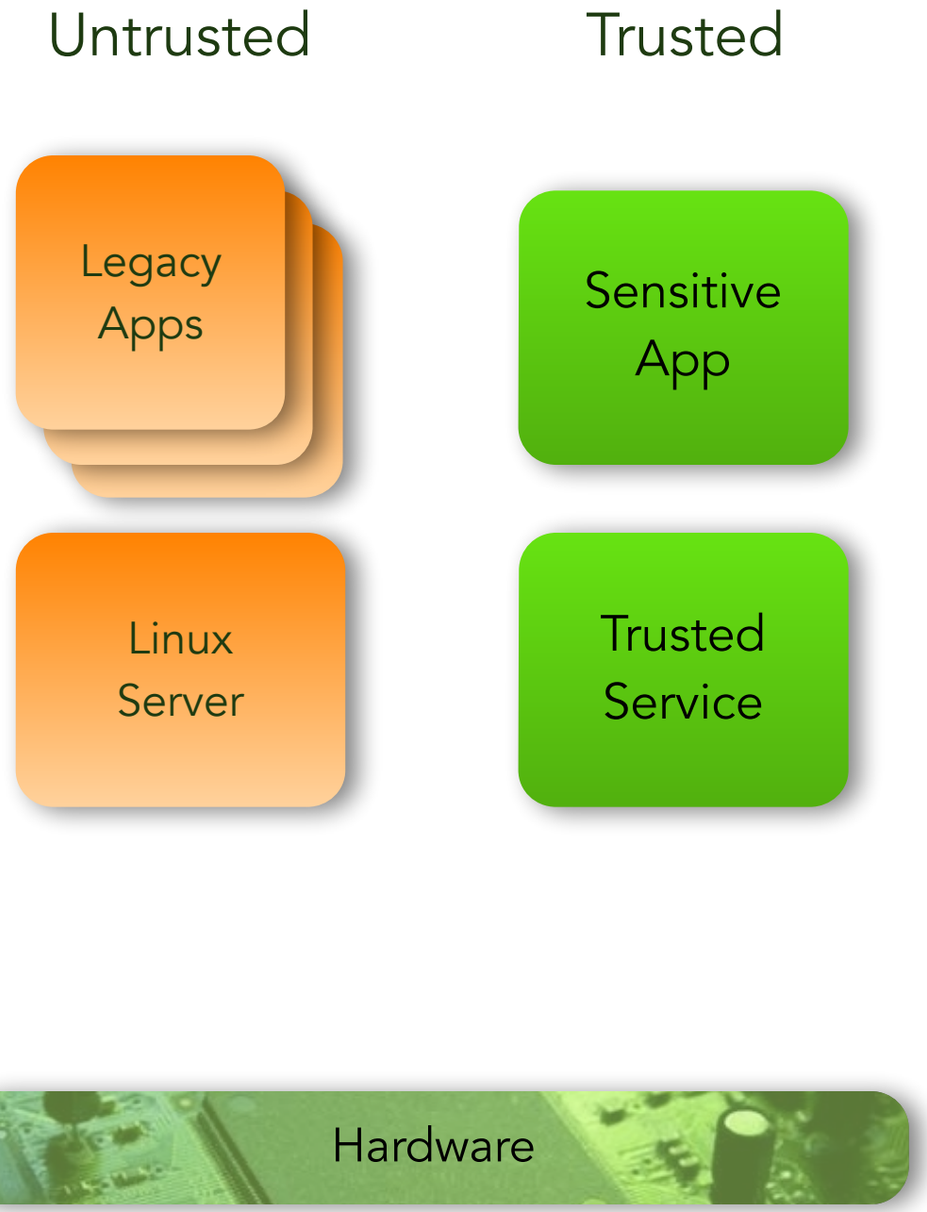
Trustworthy Computing Base

- message passing
- virtual memory
- interrupt handling
- access control

Applications

- fault isolation
- fault identification
- IP protection
- modularity

Trusted next to Untrusted



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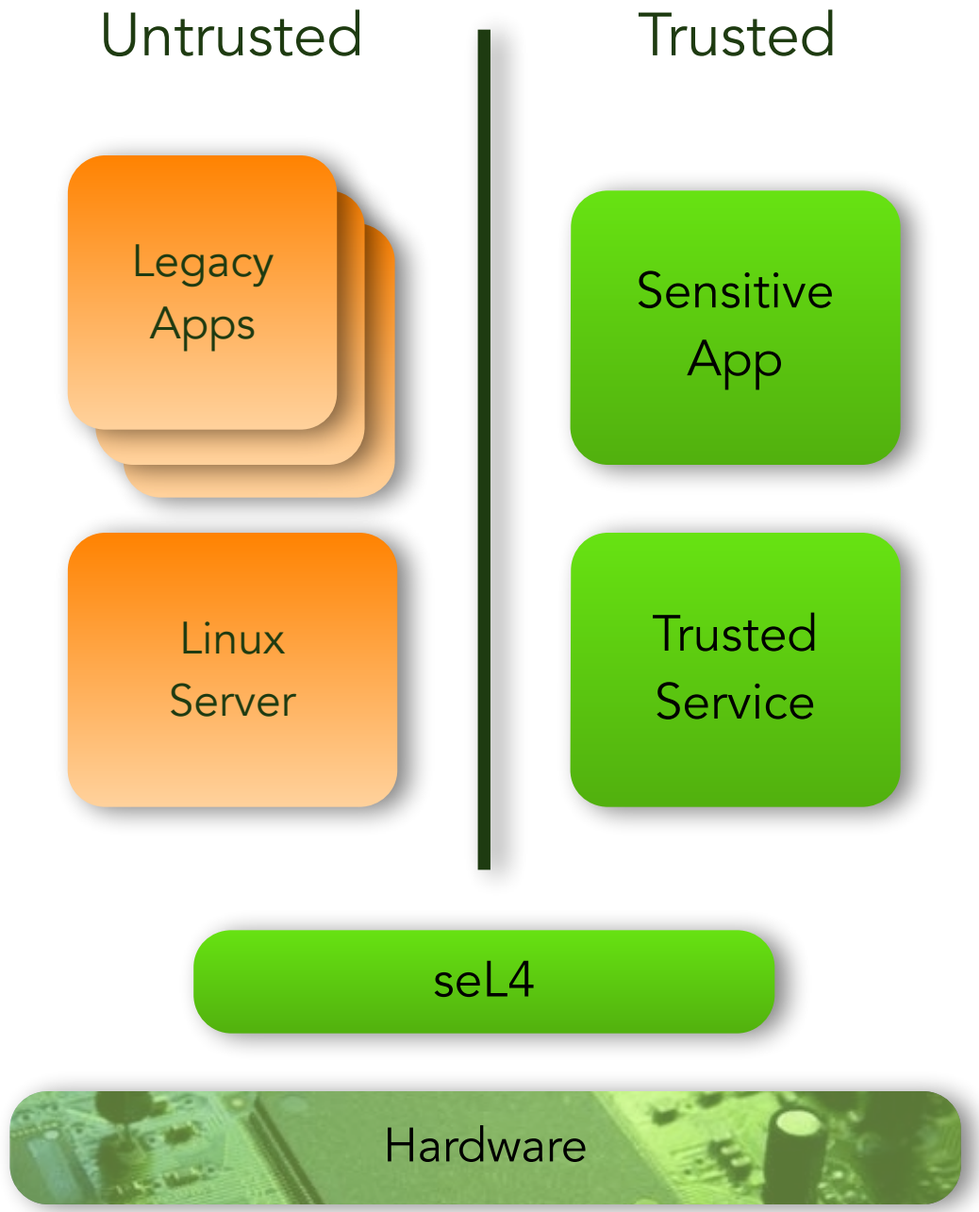
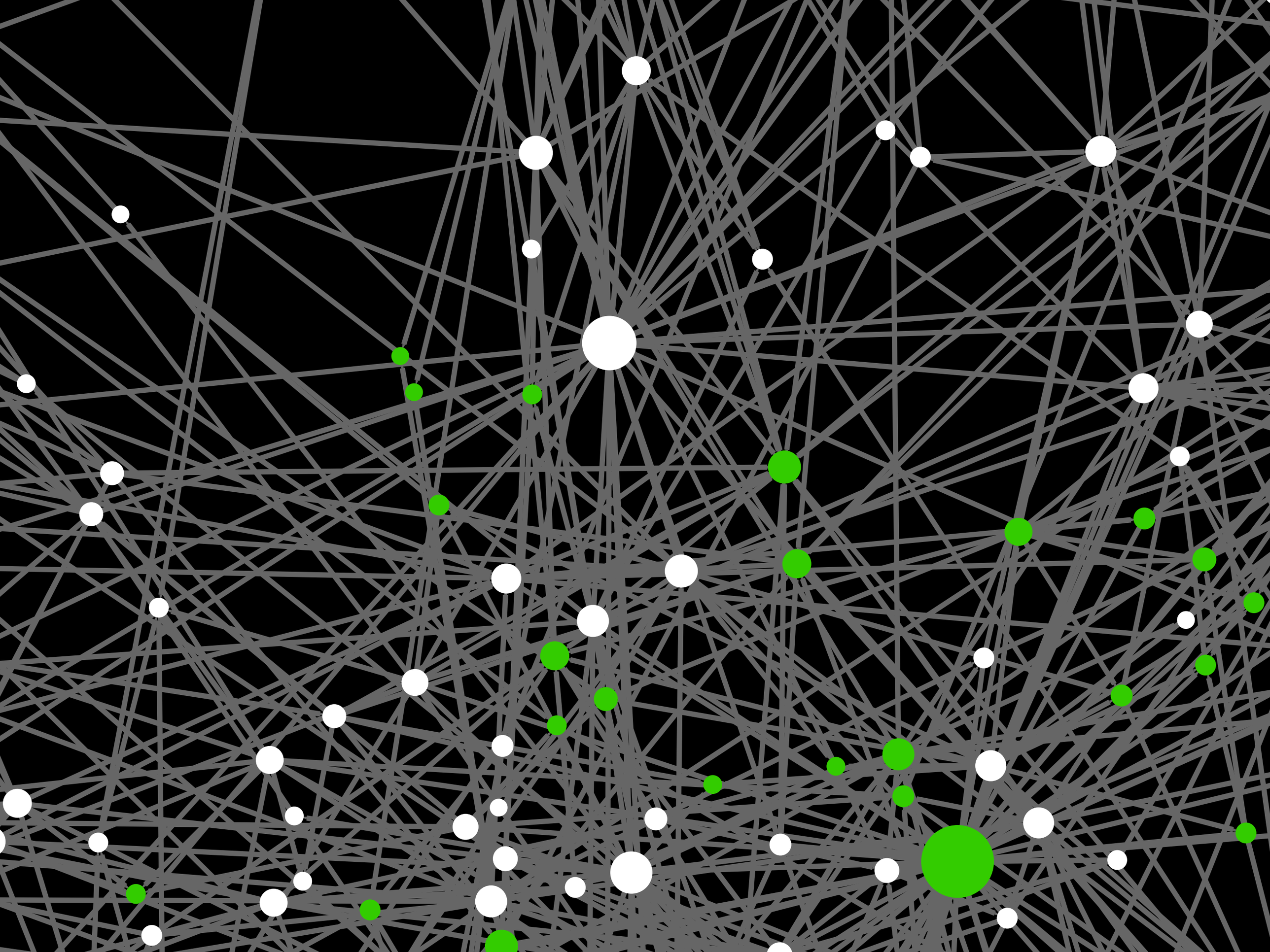
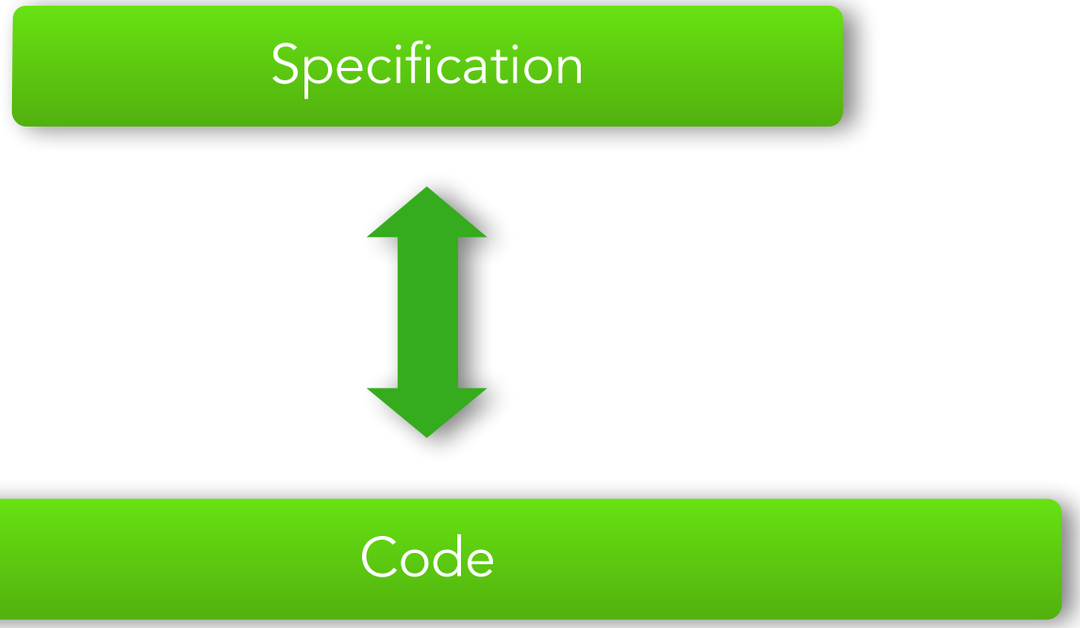





seL4

Functional Correctness Possible



Functional Correctness Possible

What

Proof

Specification

```
definition
  schedule :: unit s_monad where
  schedule ≡ do
    threads ← allActiveTCBs;
    thread ← select threads;
    switch_to_thread thread
  od
  OR switch_to_idle_thread
```

Code

Functional Correctness Possible

NICTA

What

Proof

How

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```

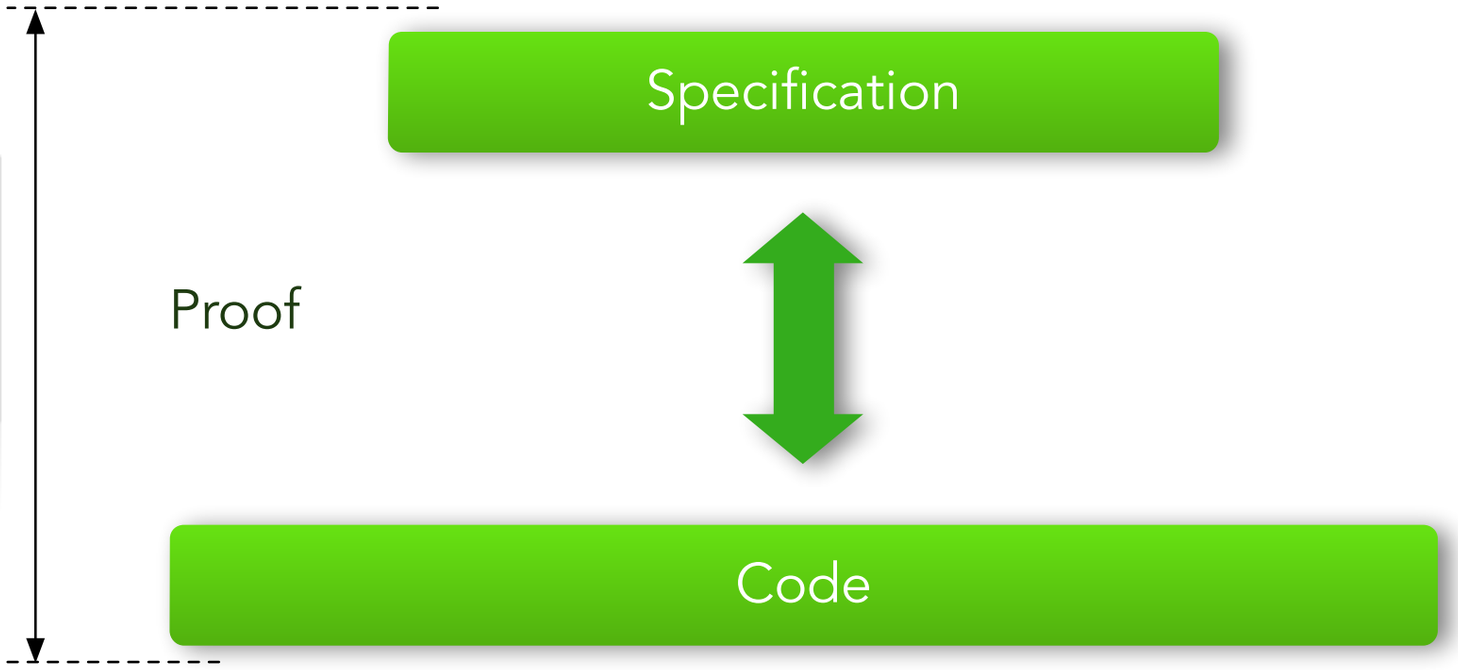
```
void
schedule(void) {
    switch ((word_t)ksSchedulerAction) {
        case (word_t)SchedulerAction_ResumeCurrentThread:
            break;

        case (word_t)SchedulerAction_ChooseNewThread:
            chooseThread();
            ksSchedulerAction = SchedulerAction_ResumeCurrentThread;
            break;

        default: /* SwitchToThread */
            switchToThread(ksSchedulerAction);
            ksSchedulerAction = SchedulerAction_ResumeCurrentThread;
            break;
    }
}

void
chooseThread(void) {
    prio_t prio;
    tcb_t *thread, *next;
```

*conditions apply



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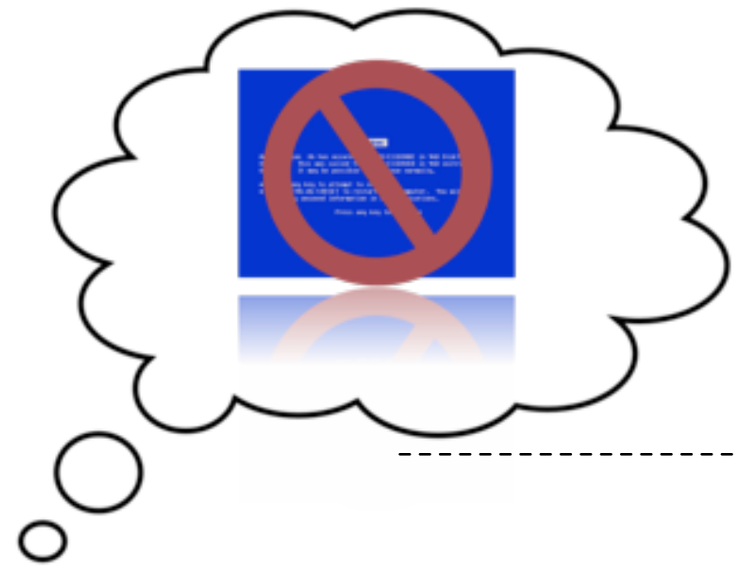

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Expectation

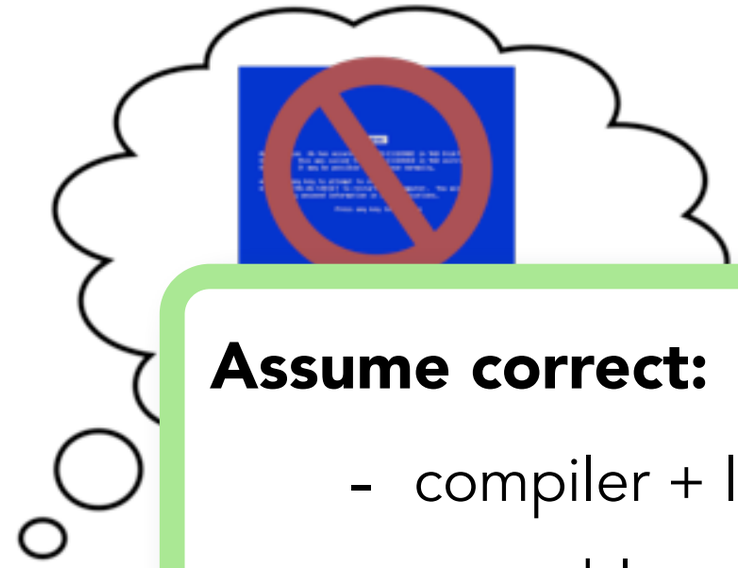
Specification

Proof

Code

Assumptions

*conditions apply



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Assume correct:

- compiler + linker (wrt. C op-sem)
- assembly code (600 loc)
- hardware (ARMv6)
- cache and TLB management
- boot code (1,200 loc)

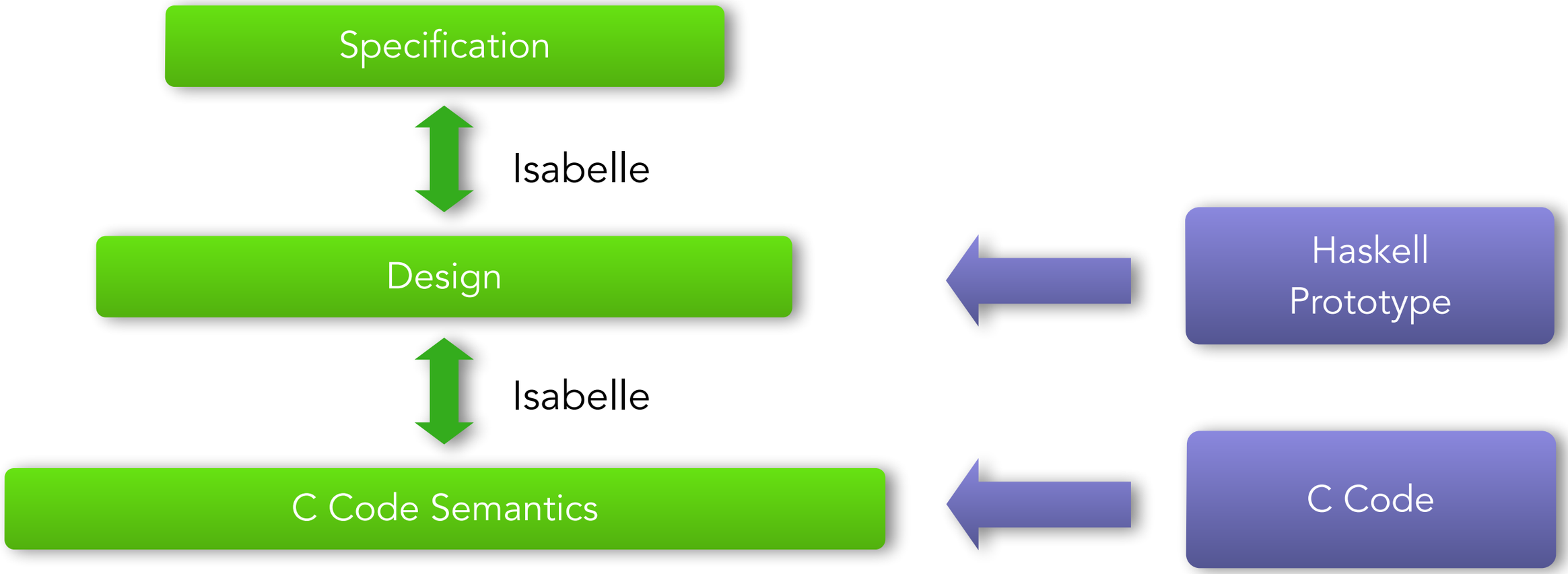
Specificatio

Proof

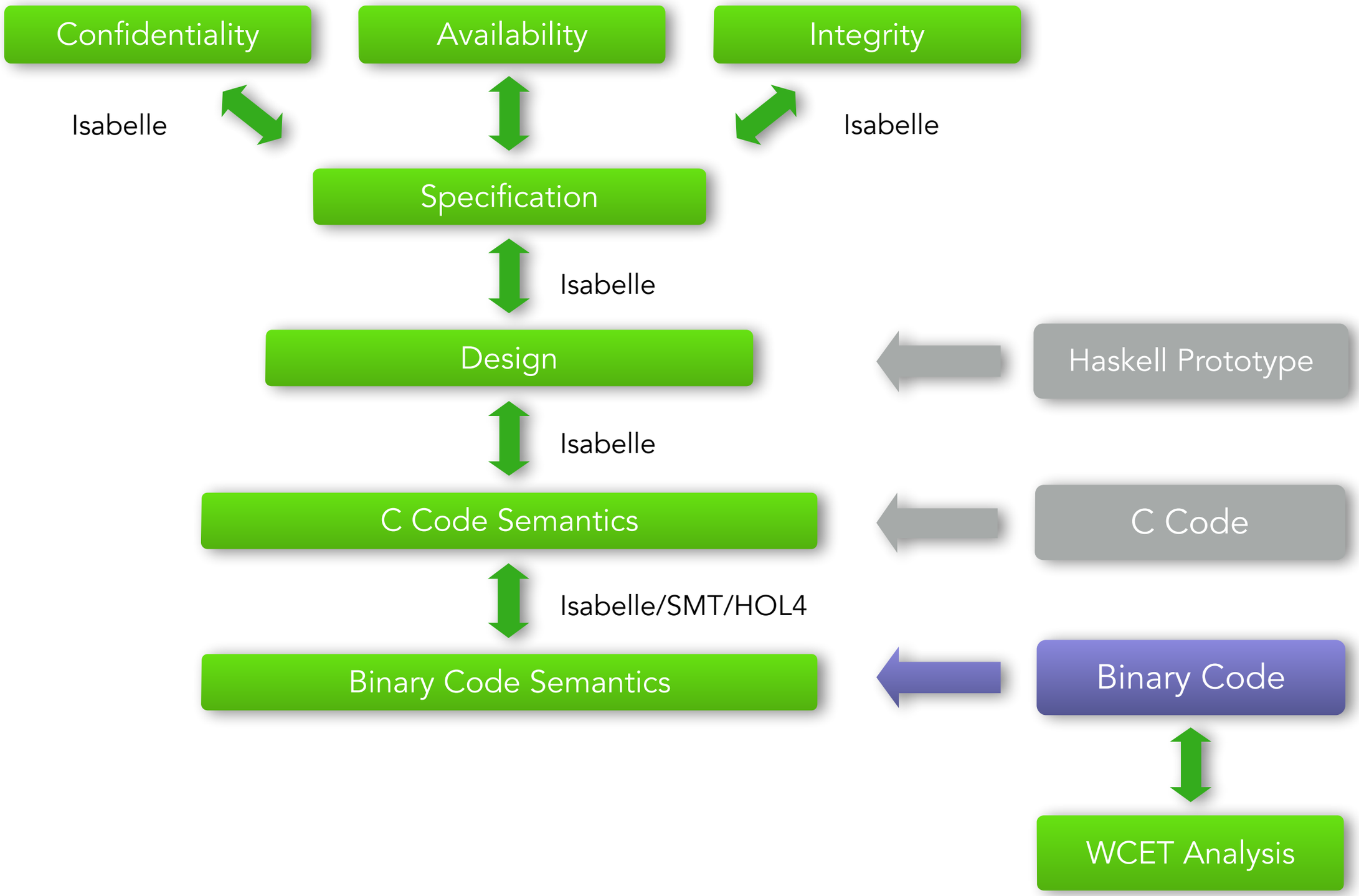
Code

Assumptions

Proof Architecture [SOSP'09]



Proof Architecture Now



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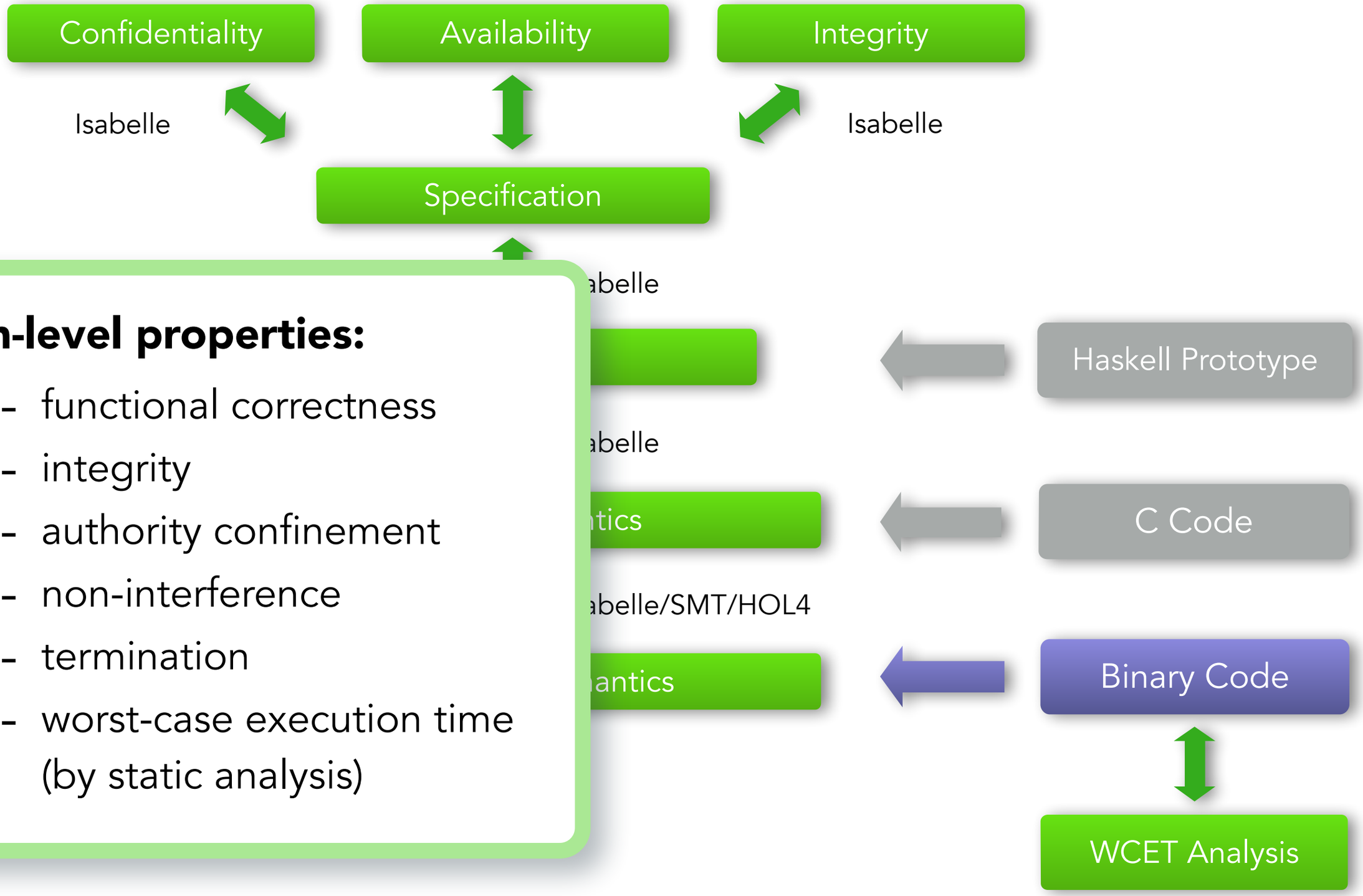

High-level properties:

- functional correctness
- integrity
- authority confinement
- non-interference
- termination
- worst-case execution time (by static analysis)

seL4: Unique Assurance

First and only general-purpose OS kernel with full functional-correctness proof – at binary level

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First and only protected-mode operating-system with complete and sound timing analysis

seL4: Unique Assurance

NICTA

First and only gener… purpose
OS kernel with ful…
correctness proof – …

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…nd confidentiality
…nt – at binary level

Open Source

in 2014

World's fastest mic…
ARM architecture

…sor deployed on
2 billion devices

First and only protected-mode operating-system with complete and sound timing analysis

Refinement Pays Off

- **Functional correctness:** 12 person years
- **Integrity+Confinement:** 10 person months
- **Non-interference:** 48 person months
- **Binary Verification:** automatic

Cost of Assurance

Cost of Assurance

- **Industry Best Practice:**
  - High assurance (Common Criteria EAL 6+):
    $1,000/LOC, model verification + testing, unoptimised
  - Low assurance (traditional embedded kernels):
    $100–200/LOC, 1–5 faults/kLOC, optimised

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- **State of the Art – seL4:**
  - $400/LOC, binary-level formal proof, optimised
  - Estimate repeat would cost half
    - about as much as unverified predecessor Pistachio!
  - Aggressive optimisation [APSys'12]
    - much faster than traditional high-assurance kernels
    - as fast as best-performing low-assurance kernels

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Formal verification getting close to traditional kernel development.

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Formal verification getting close to traditional kernel development.

Still too expensive for large-scale user code development.

Automation, Synthesis, Proof Generation

Next Step: Full System Assurance

DARPA HACMS Program:

- Provable vehicle safety
- Red Team must not be able to divert vehicle

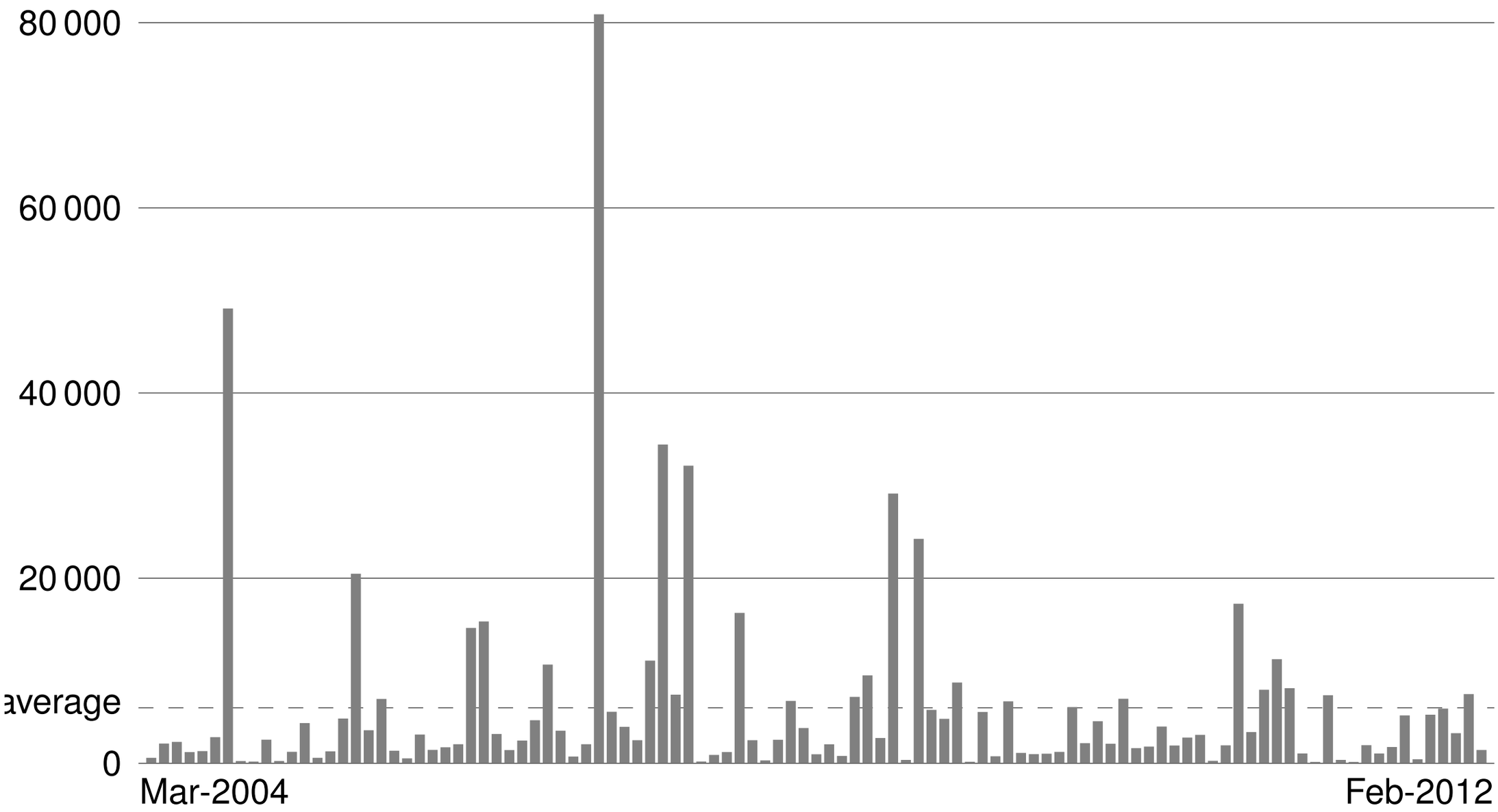
Boeing Unmanned Little Bird (AH-6)

SMACCMcopter Research Vehicle

Scale

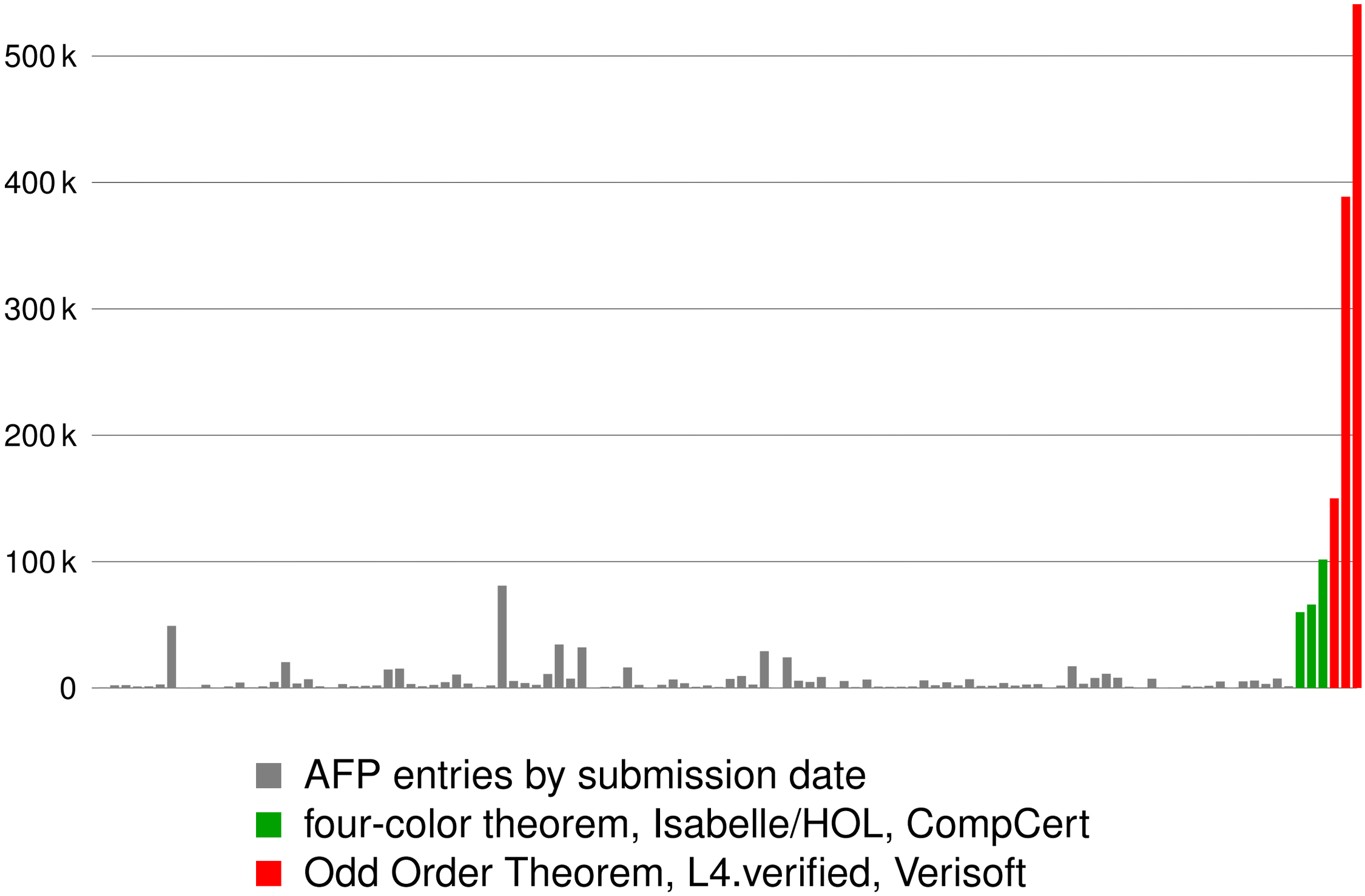
Scale

Scale



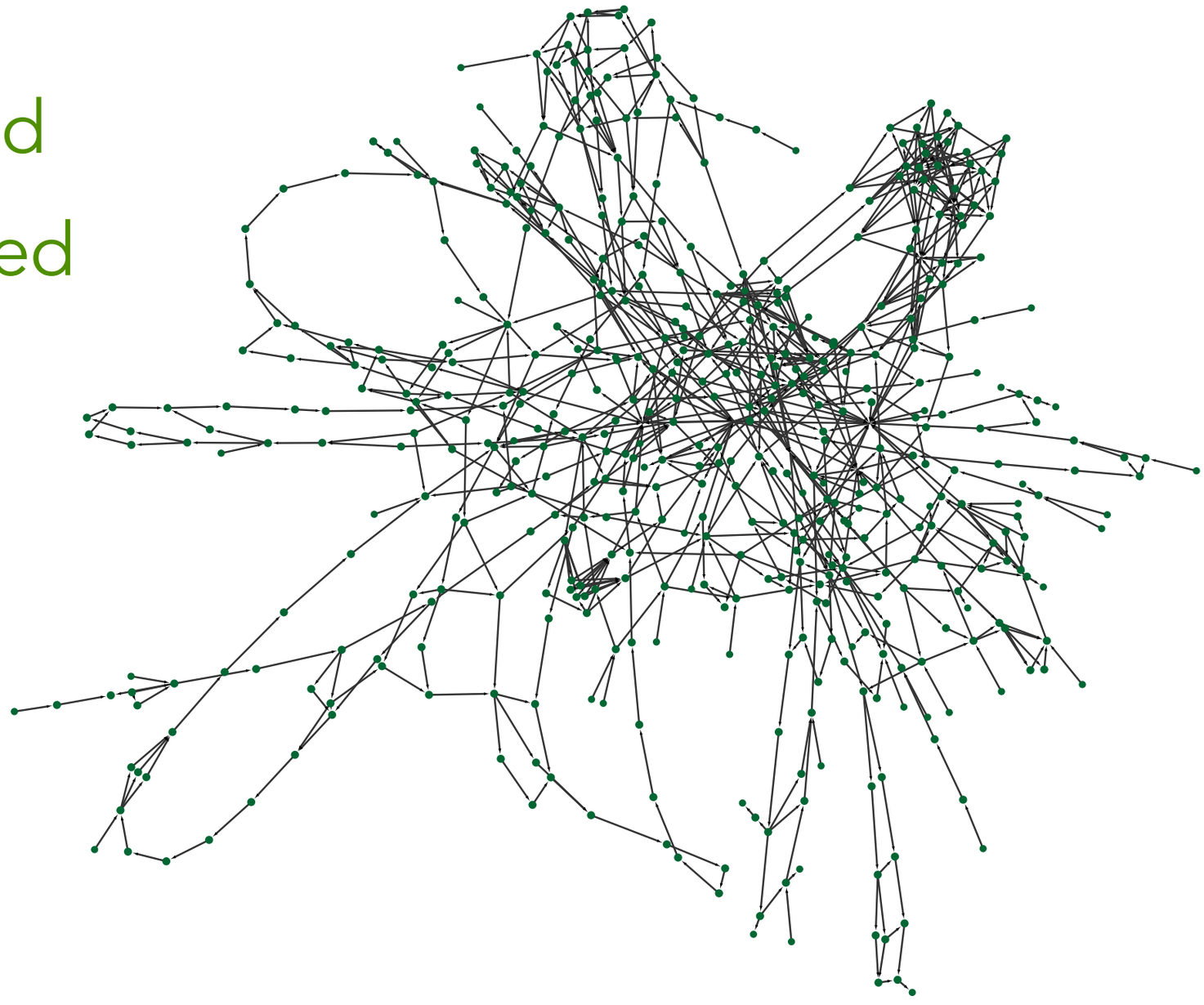
Size distribution of AFP entries in lines of proof,
sorted by submission date

Scale



Proof Introspection

- 500 files
- 22,000 lemmas stated
- 95,000 lemmas proved



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Raf's Observation

The introspection of proof and theories is an essential part of working on a large-scale verification development.

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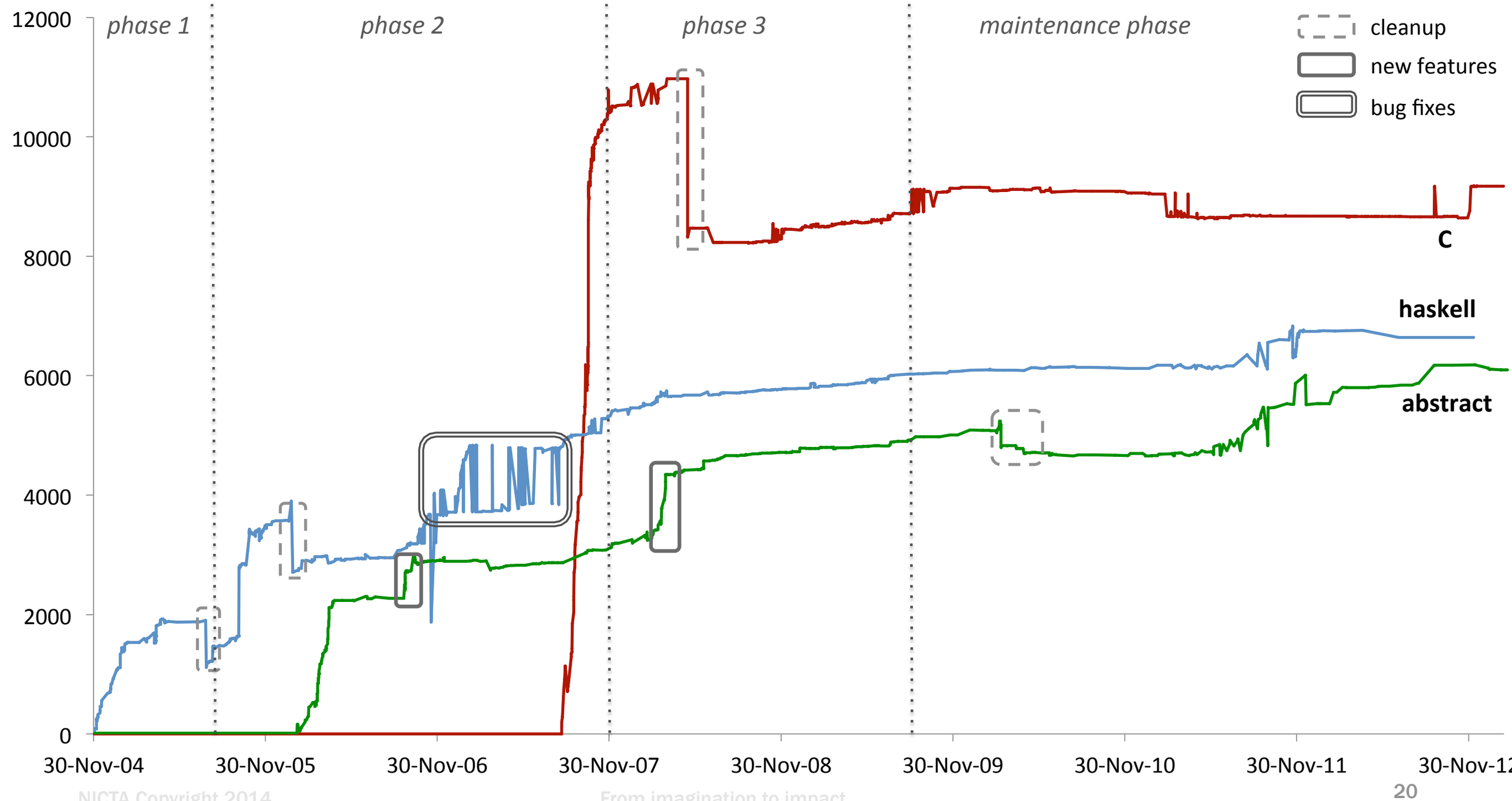
Raf's Observation

The introspection of proof and theories is an essential part of working on a large-scale verification development.

- Learning Isabelle? **Easy.**
- Learning microkernels? **Not too bad.**
- Finding your way in the 400kloc proof jungle? **Hard!**

Maintenance

- Development of seL4 code + spec artefacts (sloc)



Maintenance

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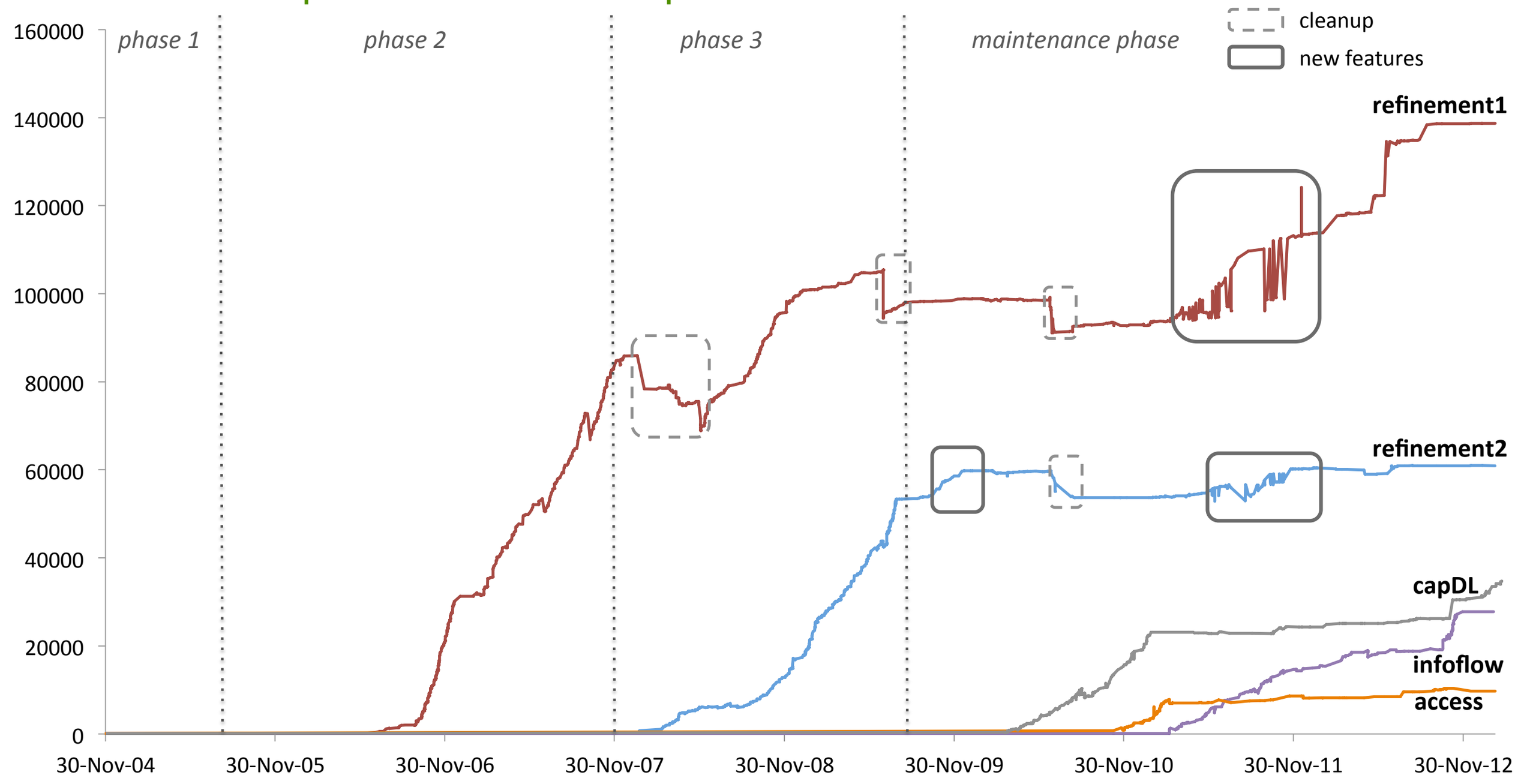
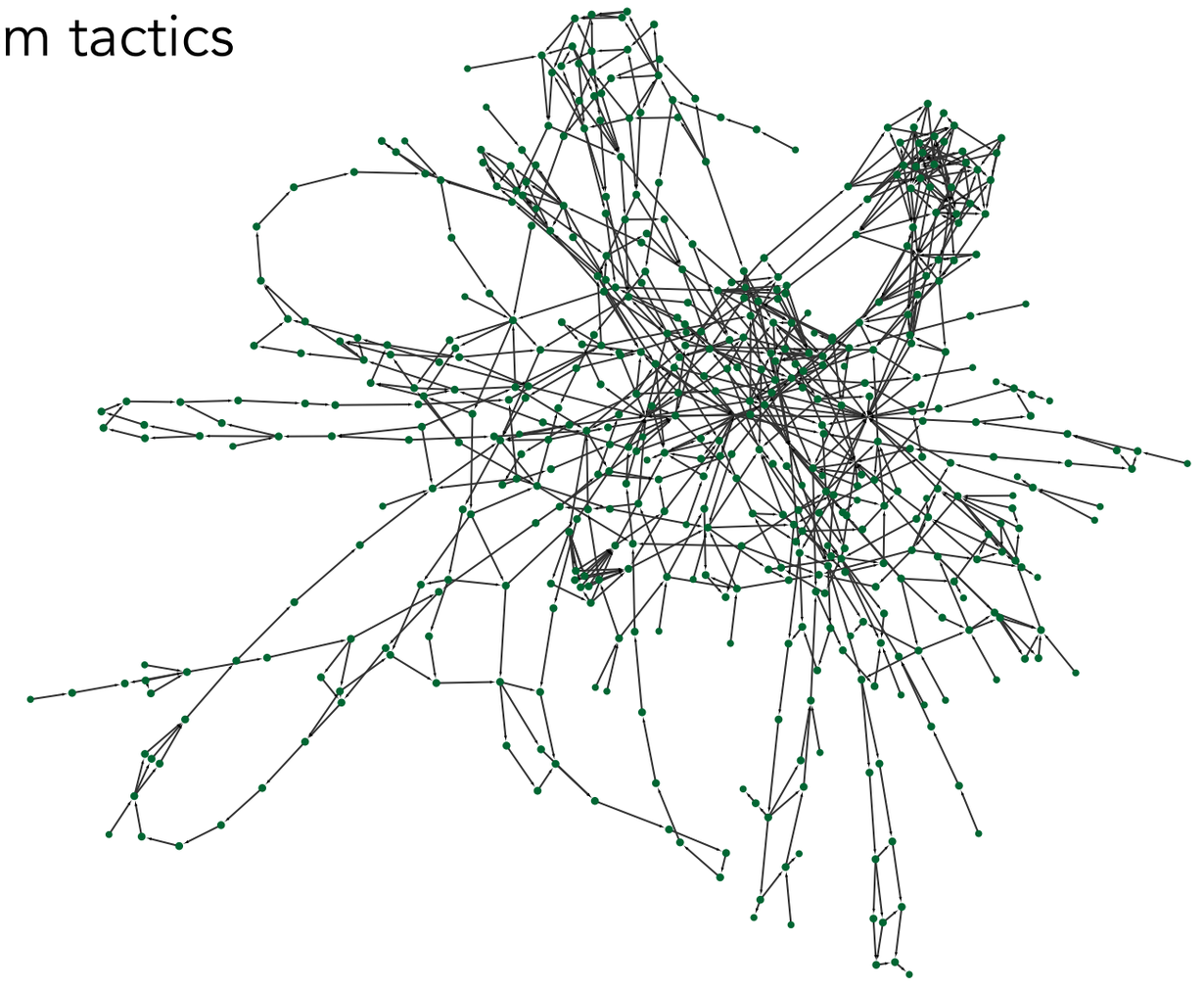


(b) Size of proofs (X: time; Y: SLOC)

Proof Development

– proof development

- decomposition of proofs over people,
- custom proof calculus,
- automating mechanical tasks, custom tactics
- proof craft



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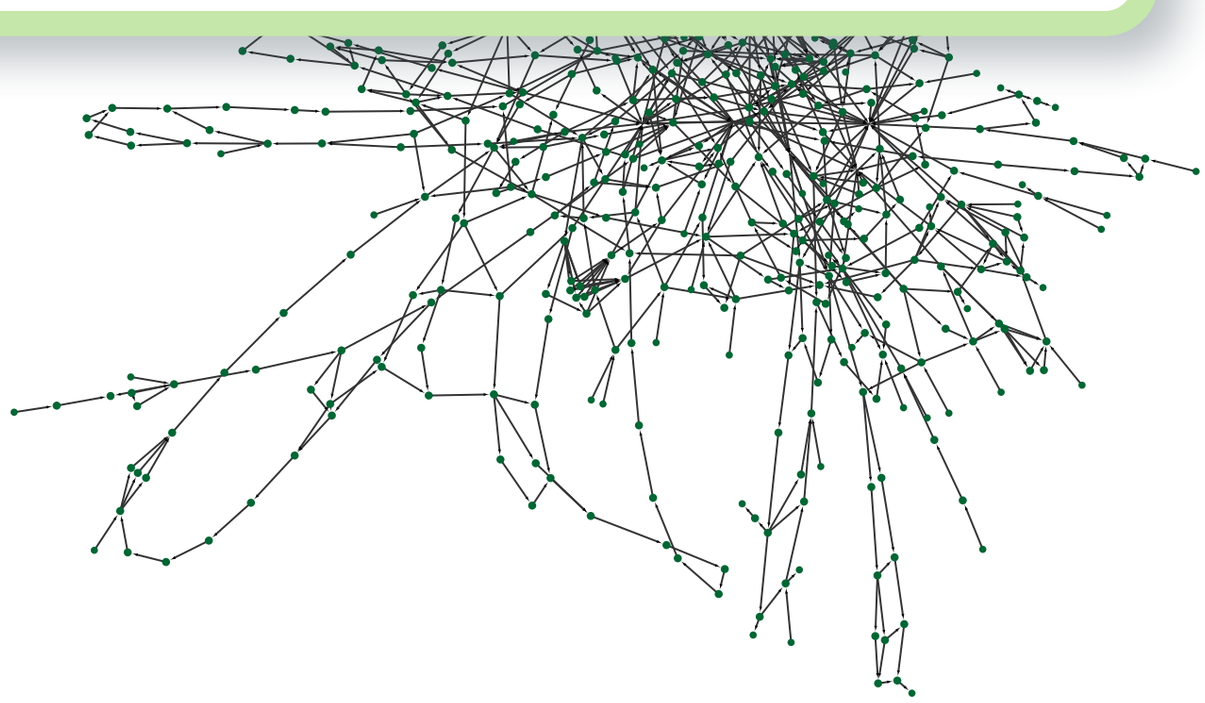
Automating "donkey work" allows attention and effort to be focussed where most needed – but it must be done judiciously.



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- non-local change,
- speculative change,
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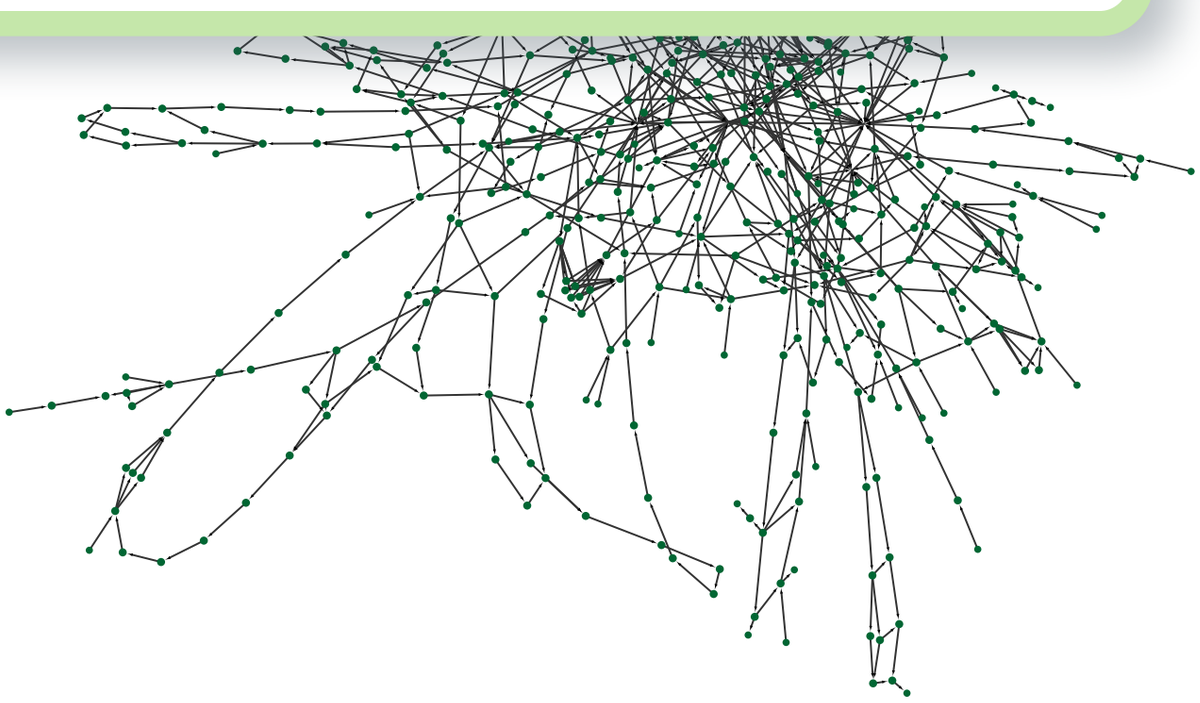

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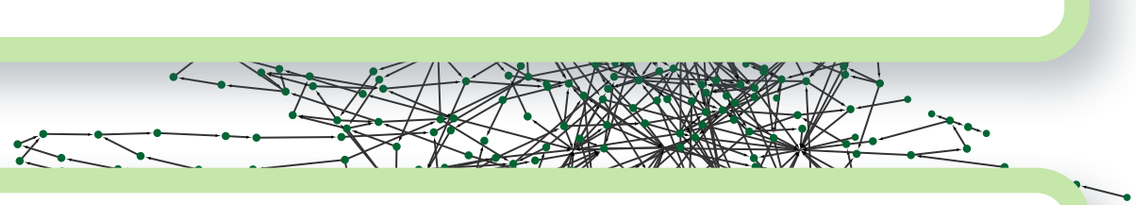

Matthias' Conjecture

Over the years, I must have waited weeks for Isabelle. Productivity hinges on a short edit-check cycle; for that, I am even willing to (temporarily) sacrifice soundness.

Problems of Scale

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– proof maintenance

- changes, updates, new proofs, new features
- automated regression, keep code in sync
- refactoring
- simplification

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Dan's Conclusion

Verification is fast, maintenance is forever.

Research Challenges

Software vs Proof Engineering

- Is Proof Engineering a thing?
  - Google Scholar:
    - “software engineering” 1,430,000 results

Software vs Proof Engineering

NICTA

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Software vs Proof Engineering

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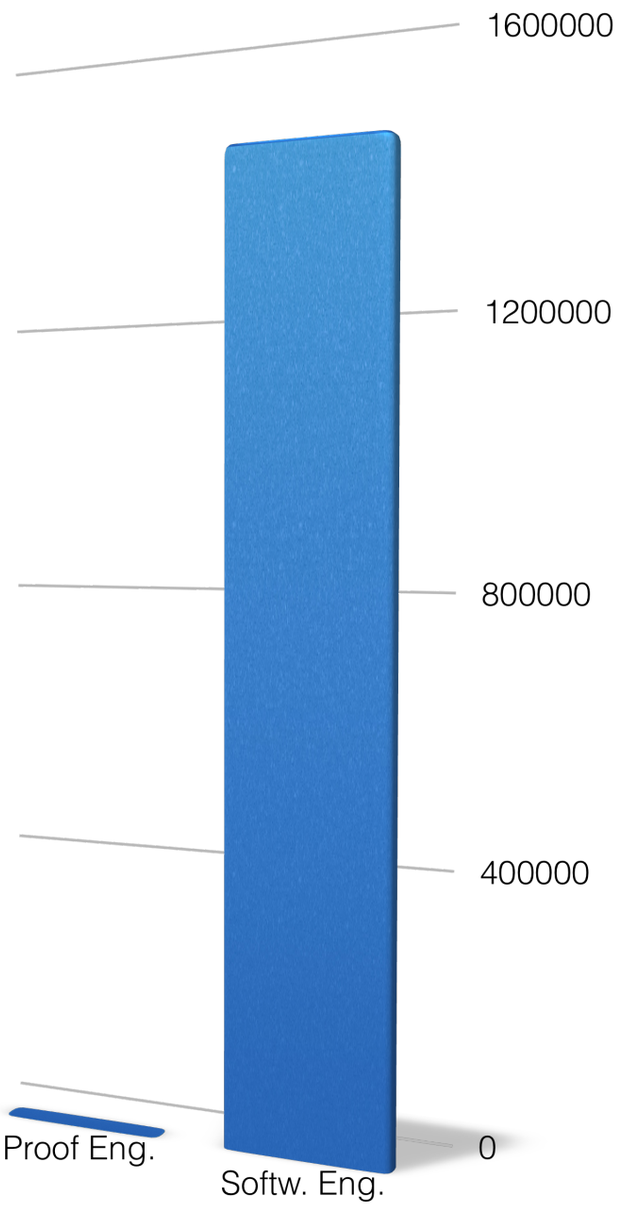
Includes

"The Fireproof Building" and

"Influence of water permeation and analysis of treatment for the Longmen Grottoes"

Proof Engineering is The Same

- Same kind of artefacts:
  - lemmas are functions, modules are modules
  - code gets big too
  - version control, regressions, refactoring and IDEs apply



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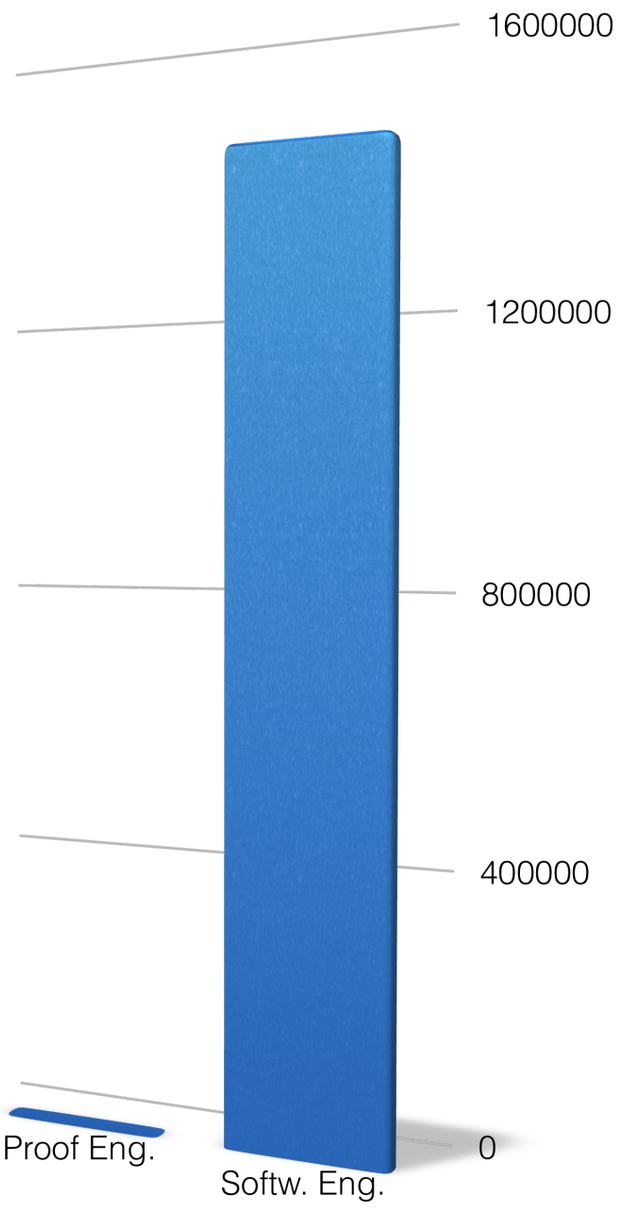
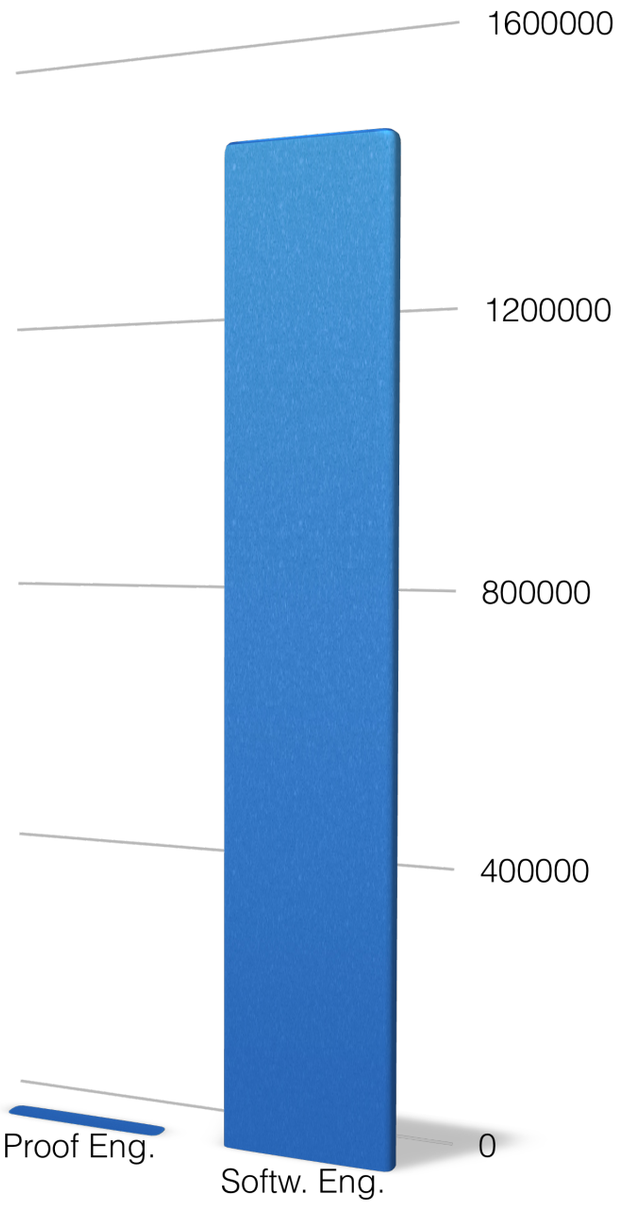


- Same kind of problems
  - managing a large proof base over time
  - deliver a proof on time within budget
  - dependencies, interfaces, abstraction, etc

Proof Engineering is Different

- But: New Properties and Problems



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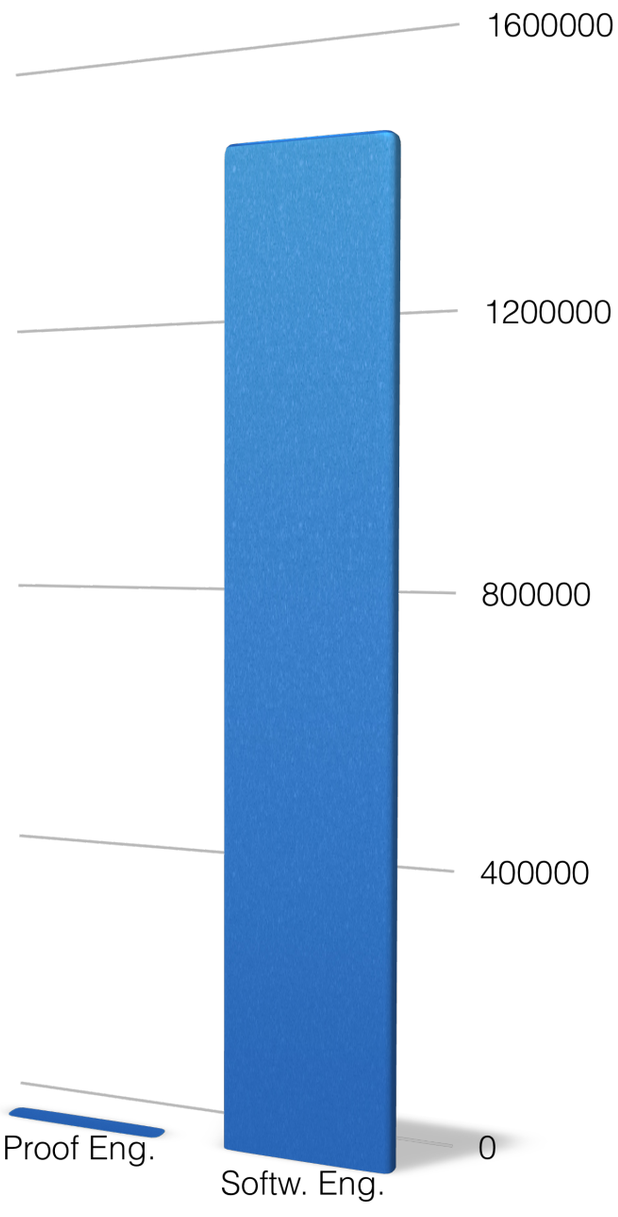
    - 95% proof: no such thing



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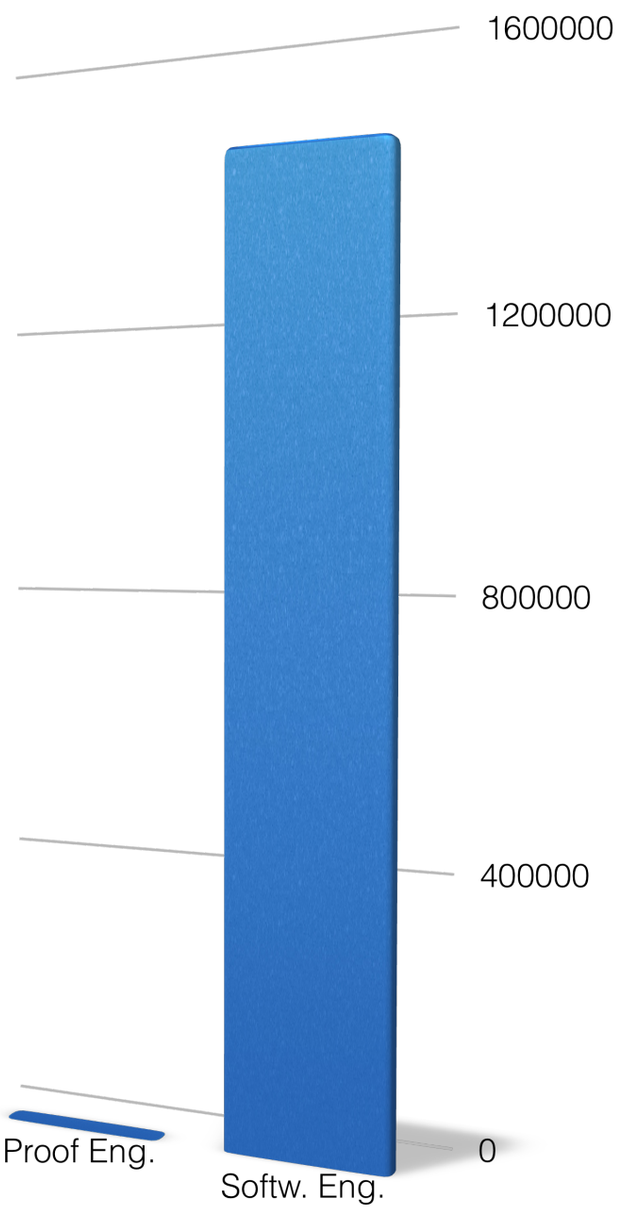

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    - Performance less critical
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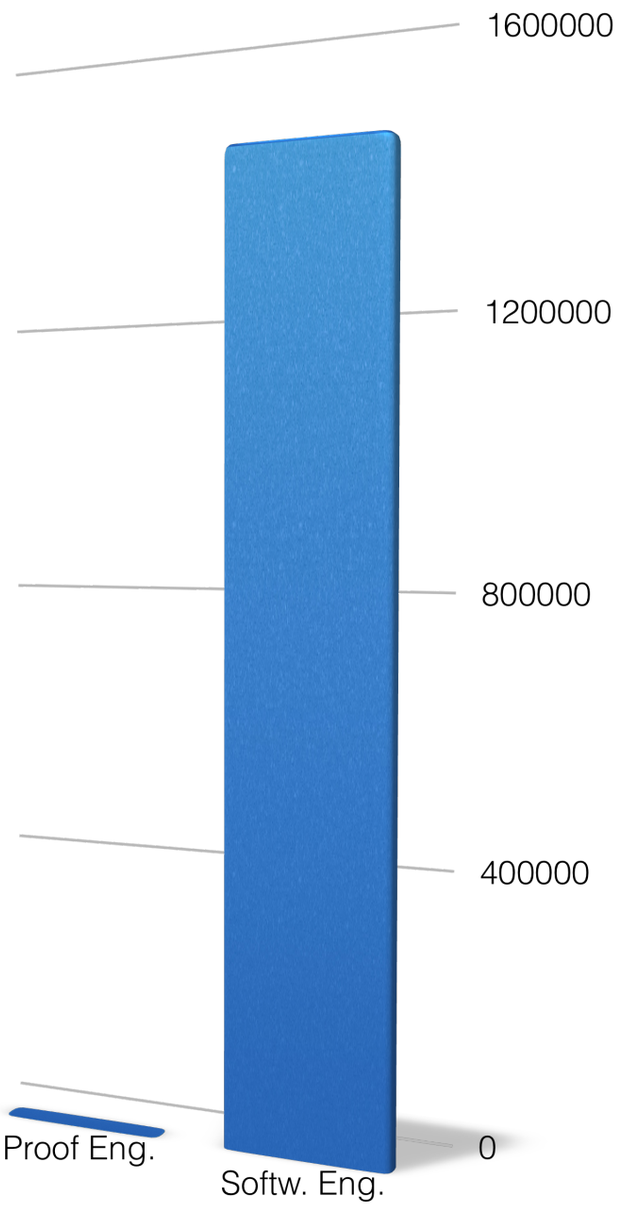

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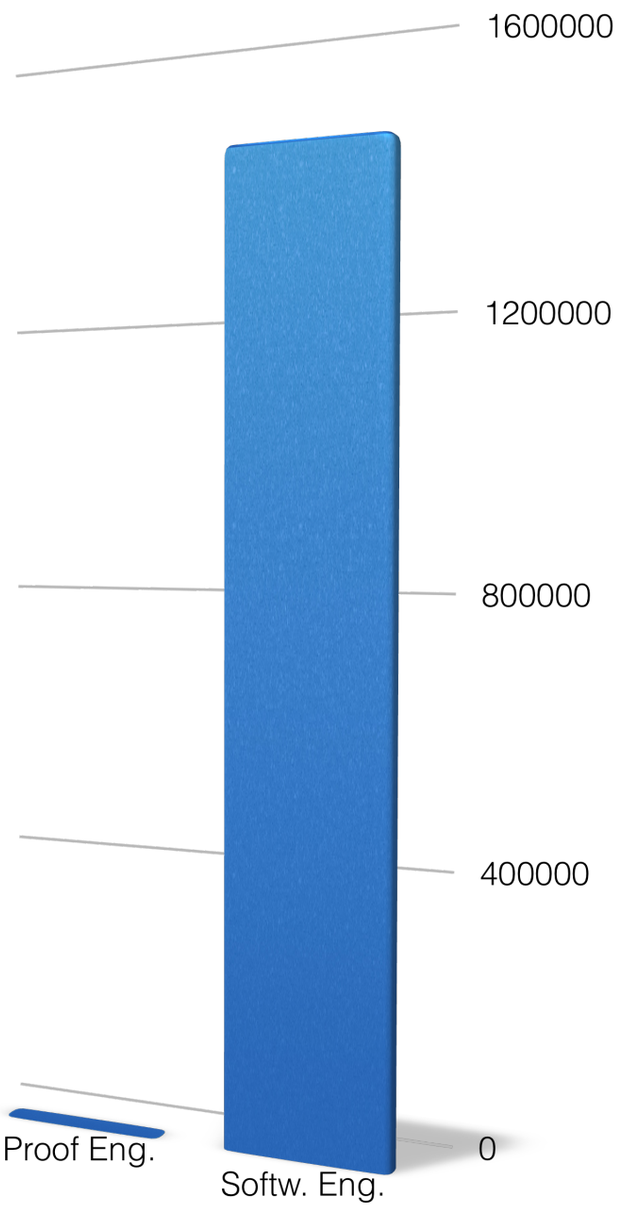
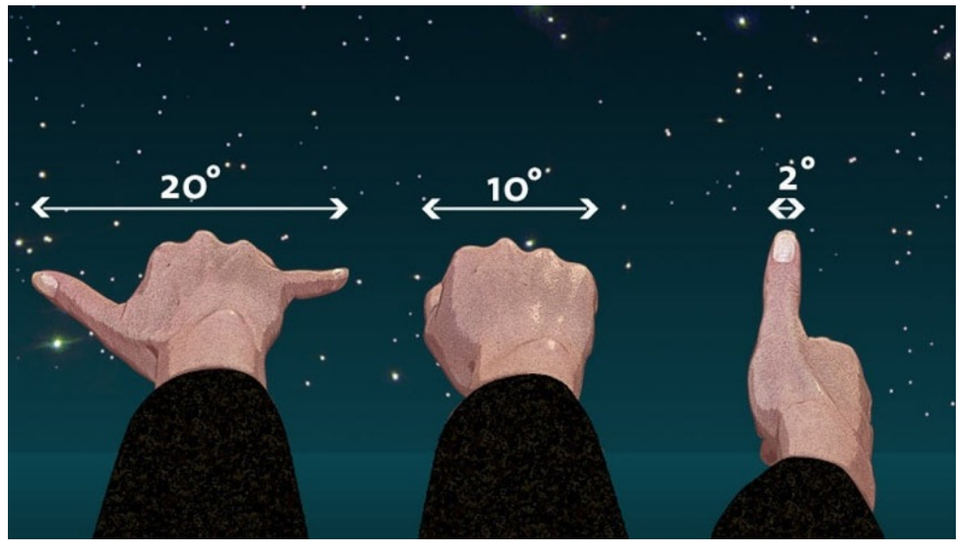
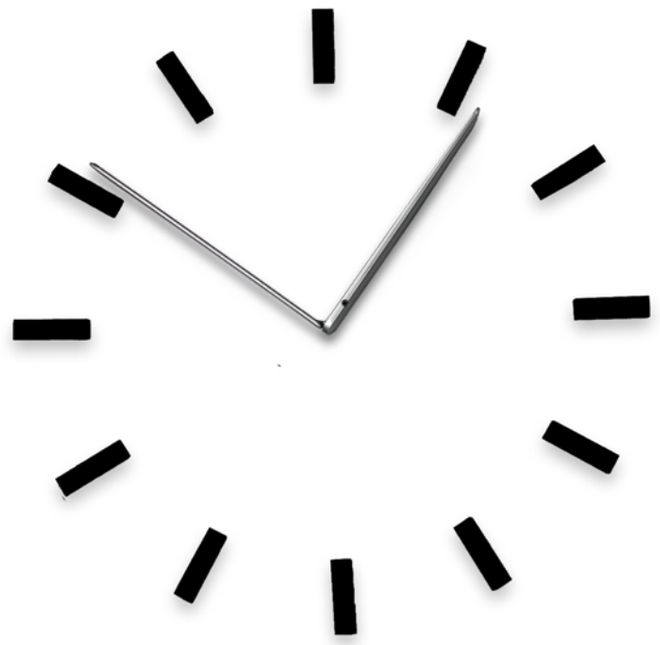
    - Proof Irrelevance
  - More semantic context
    - Much more scope for automation



Deliver within Time and Budget

- Estimation:
  - time and effort
  - how precisely, with which confidence?
  - how early?





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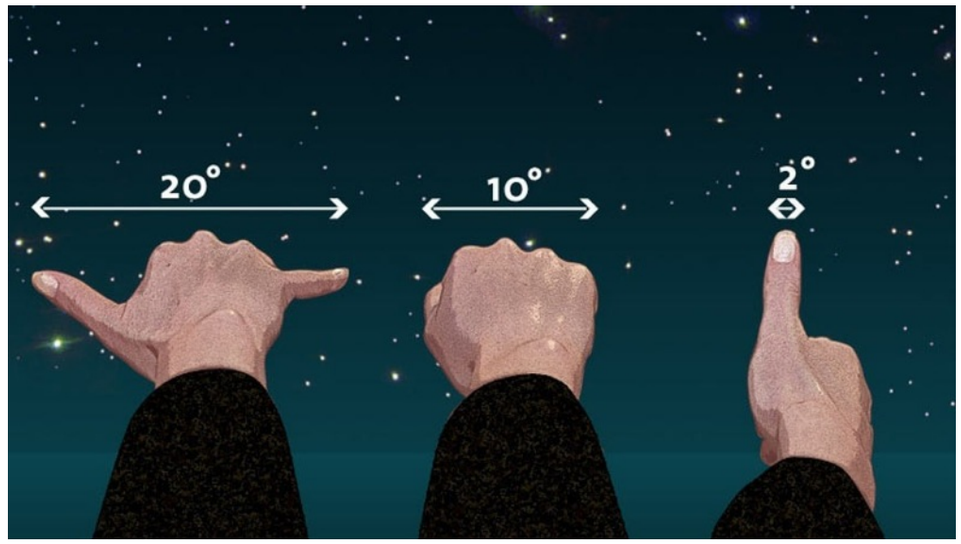
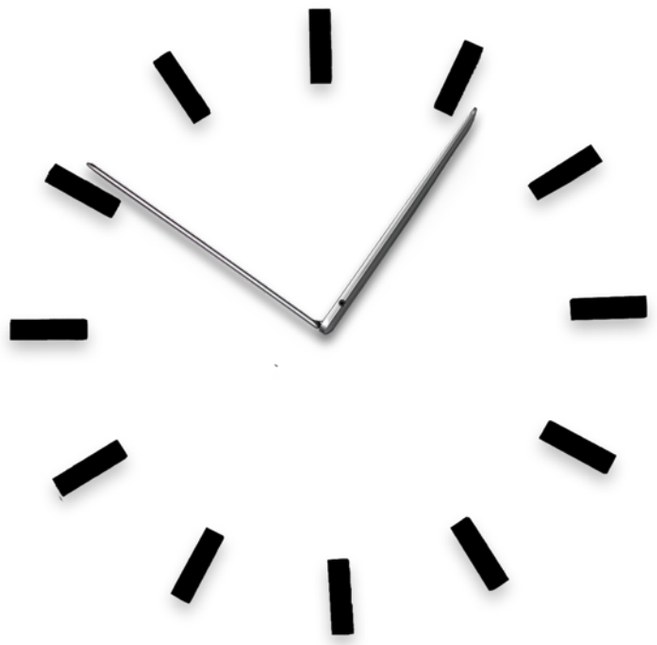
  - related to effort?





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  - time and effort
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- Size of artefacts
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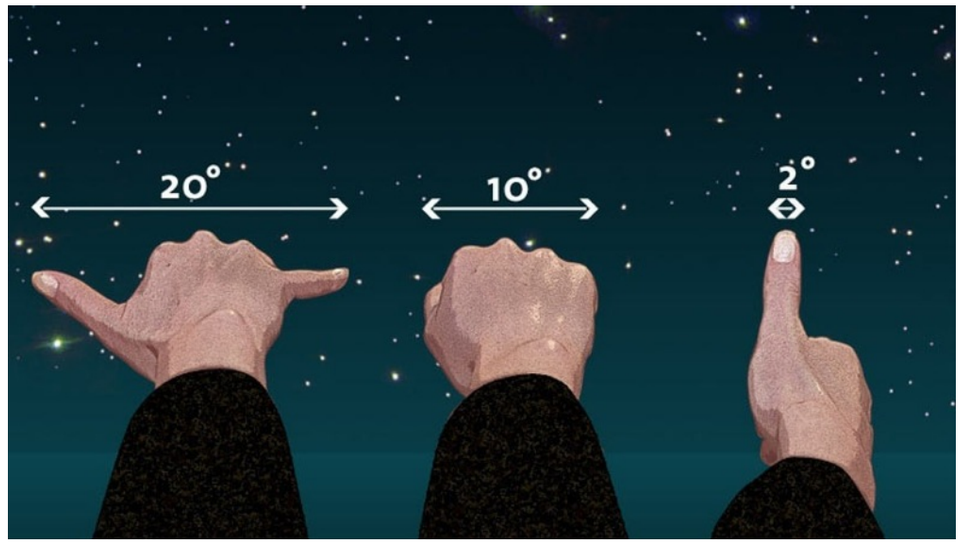
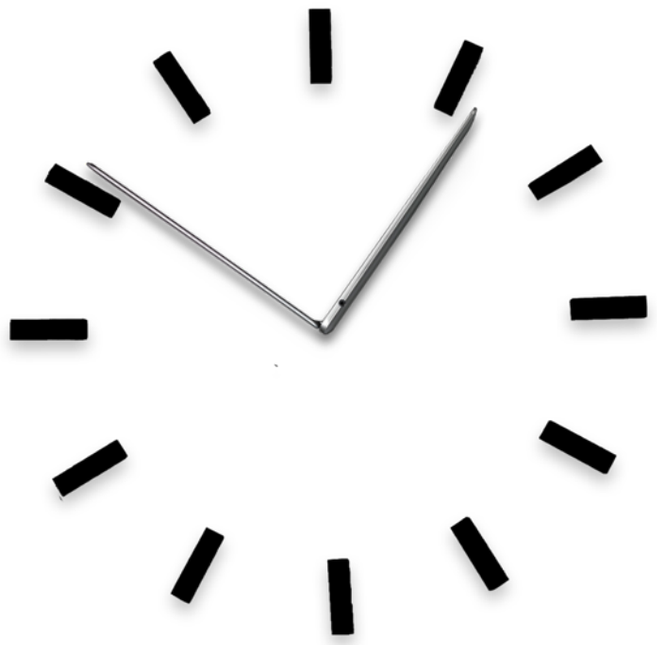
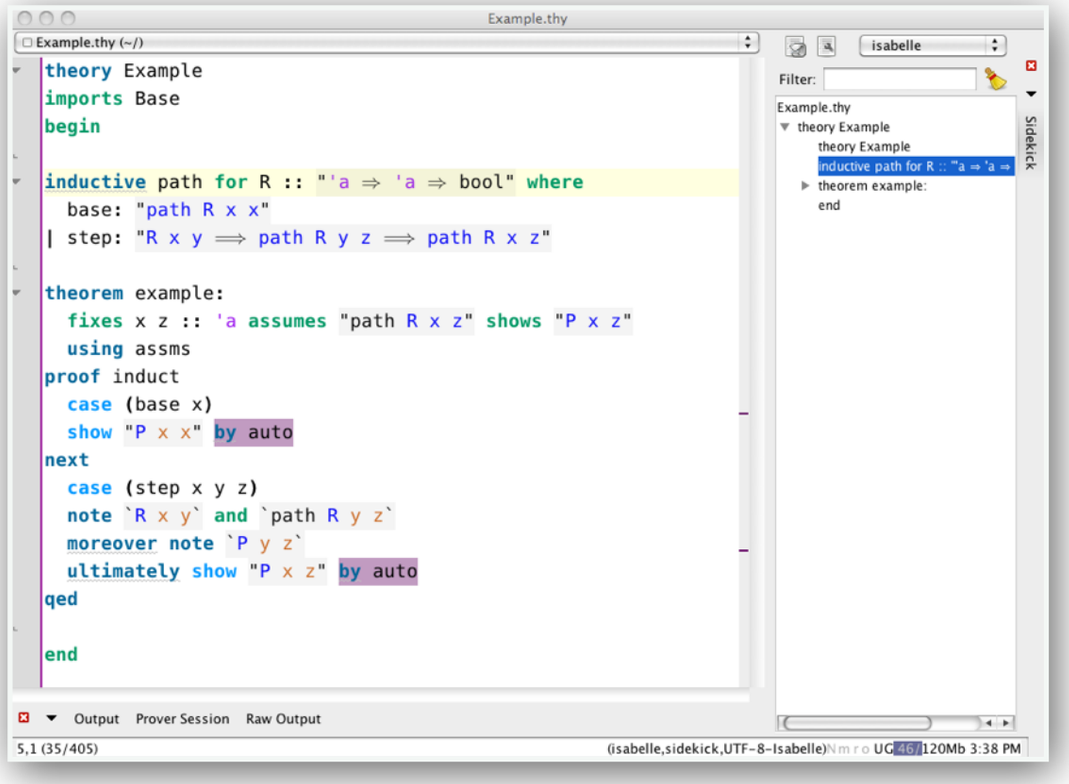
  - related to effort?
- Complexity
  - from initial artefacts?
  - which influence?





Proof Engineering Tools

- User Interface
  - could proof IDEs be more powerful than code IDEs?
  - more semantic information
  - proof completion and suggestion?



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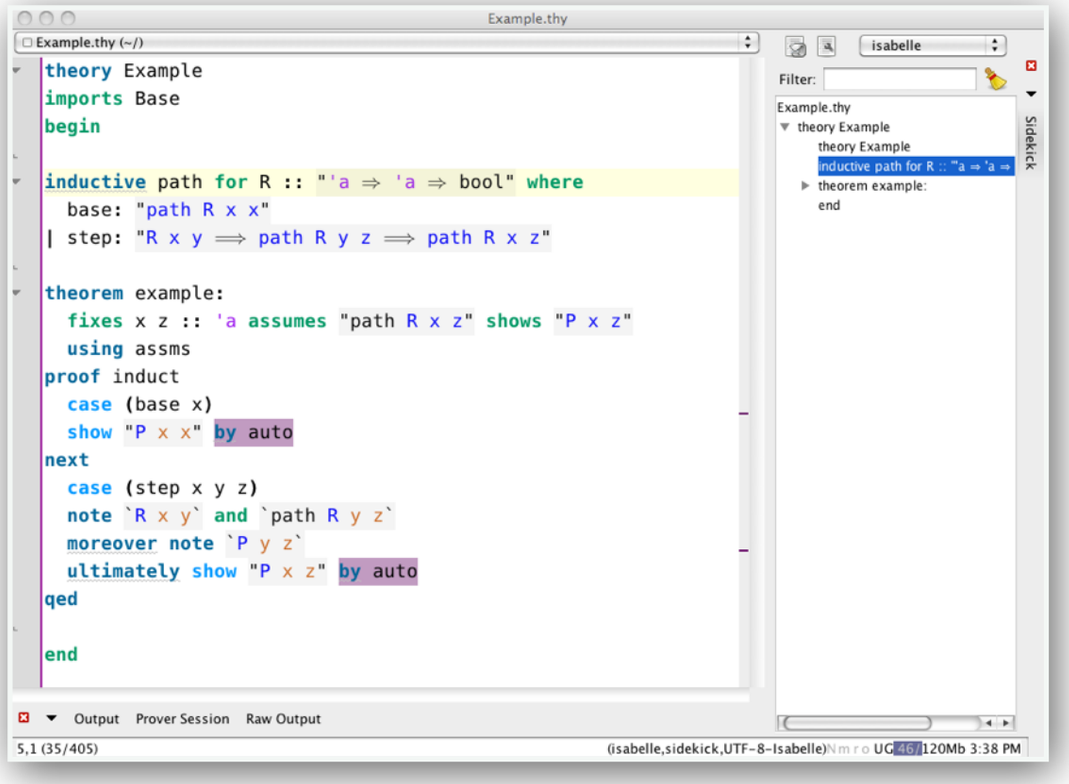
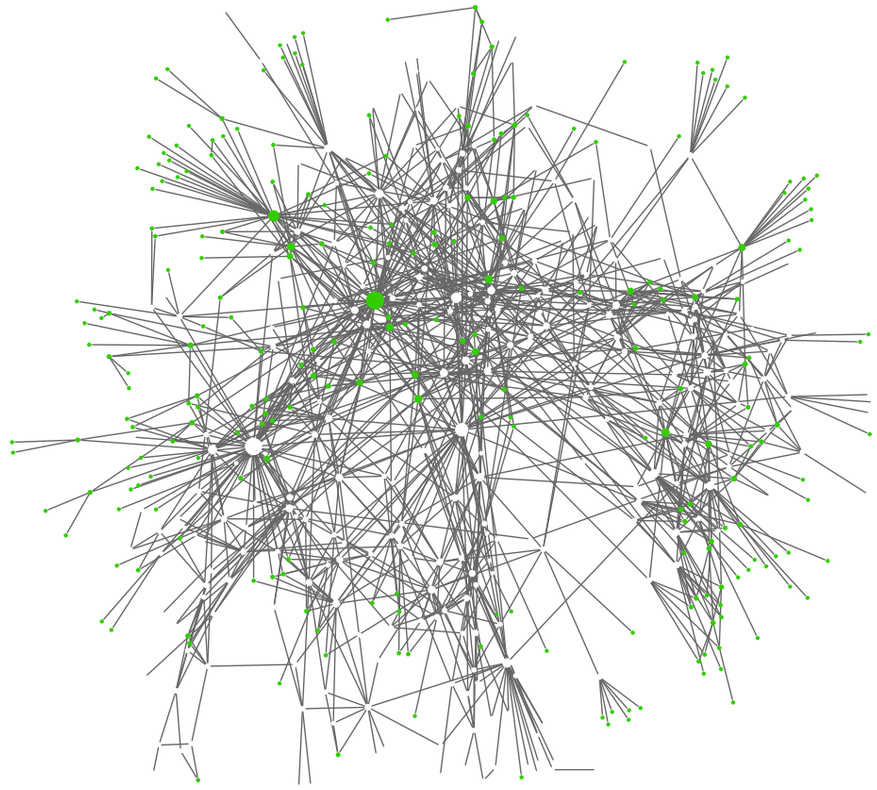


- Refactoring
  - less constrained,
    new kinds of refactoring possible, e.g.
    - move to best position in library
    - generalise lemma
    - recognise proof patterns

Proof Patterns

- Large-scale Libraries
  - architecture:
    - layers, modules, components, abstractions, genericity
  - proof interfaces
  - proof patterns



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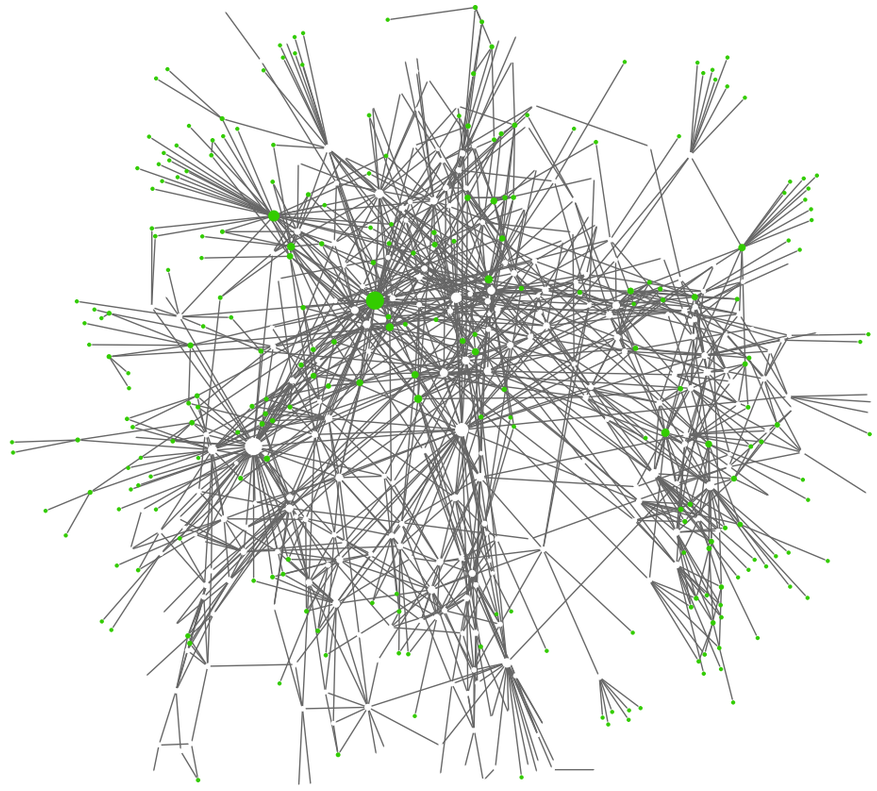
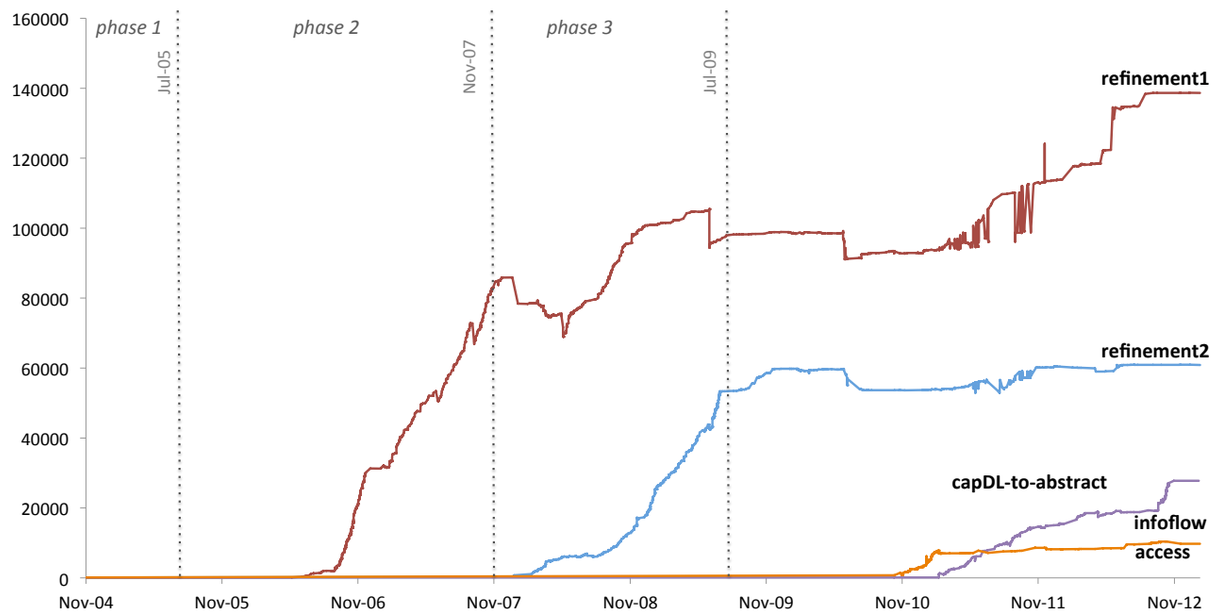


- Technical Debt
  - what does a clean, maintainable proof look like?
  - which techniques will make future change easier?
  - readability important? is documentation?

Proof Engineering “Laws”

- Are there Proof Engineering Laws?



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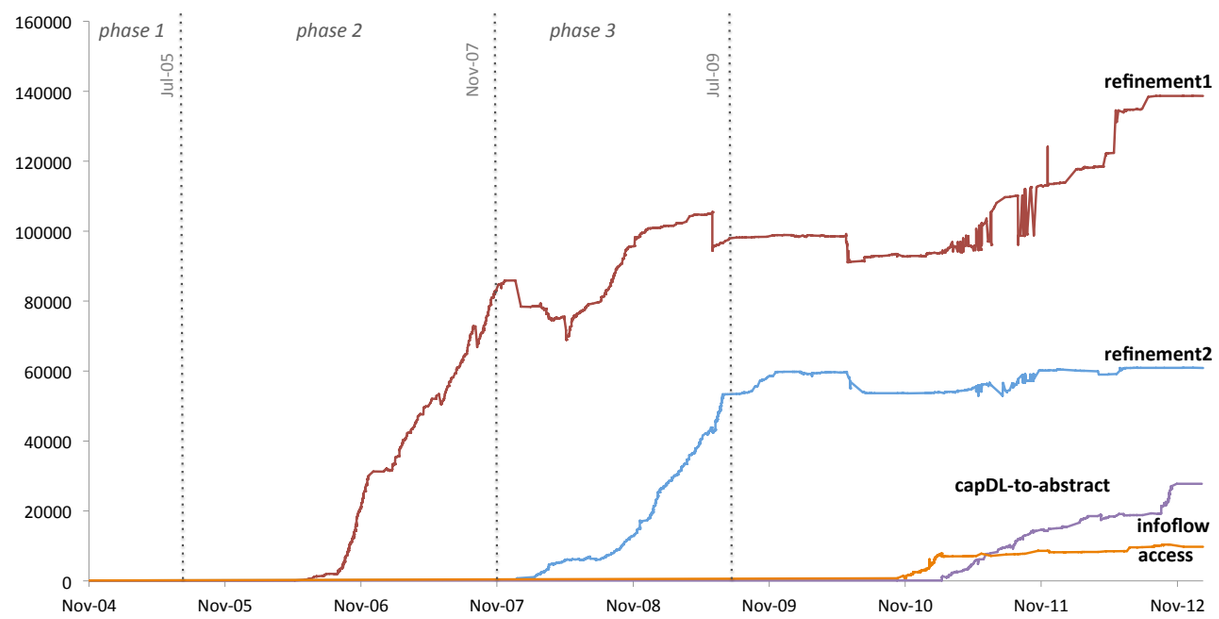

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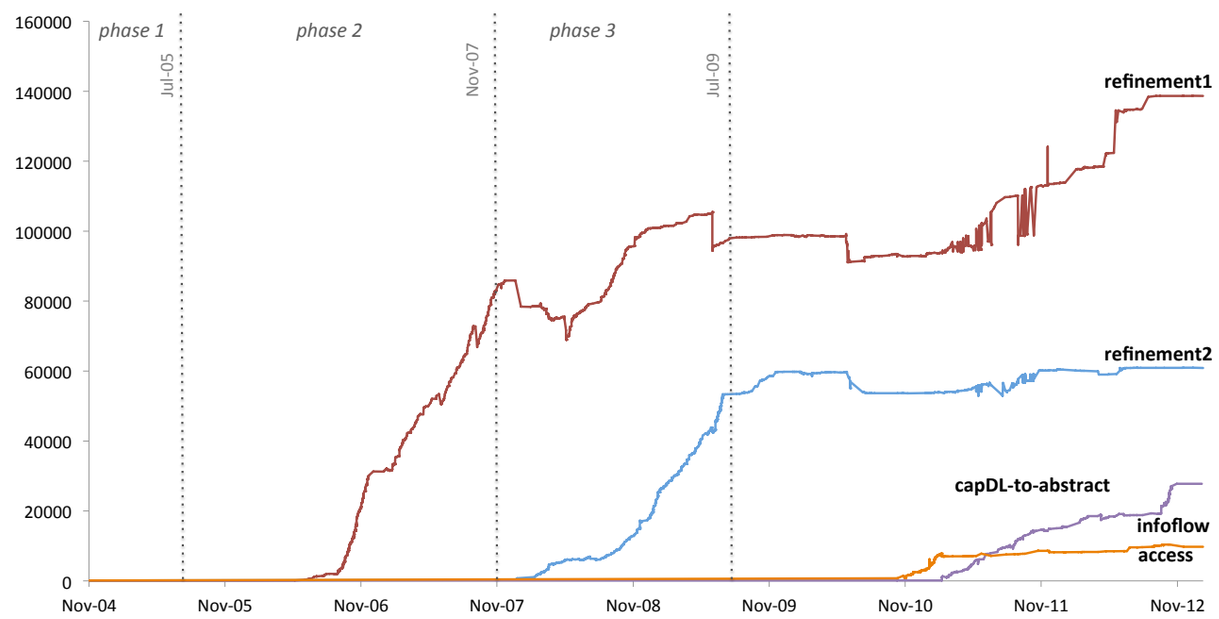

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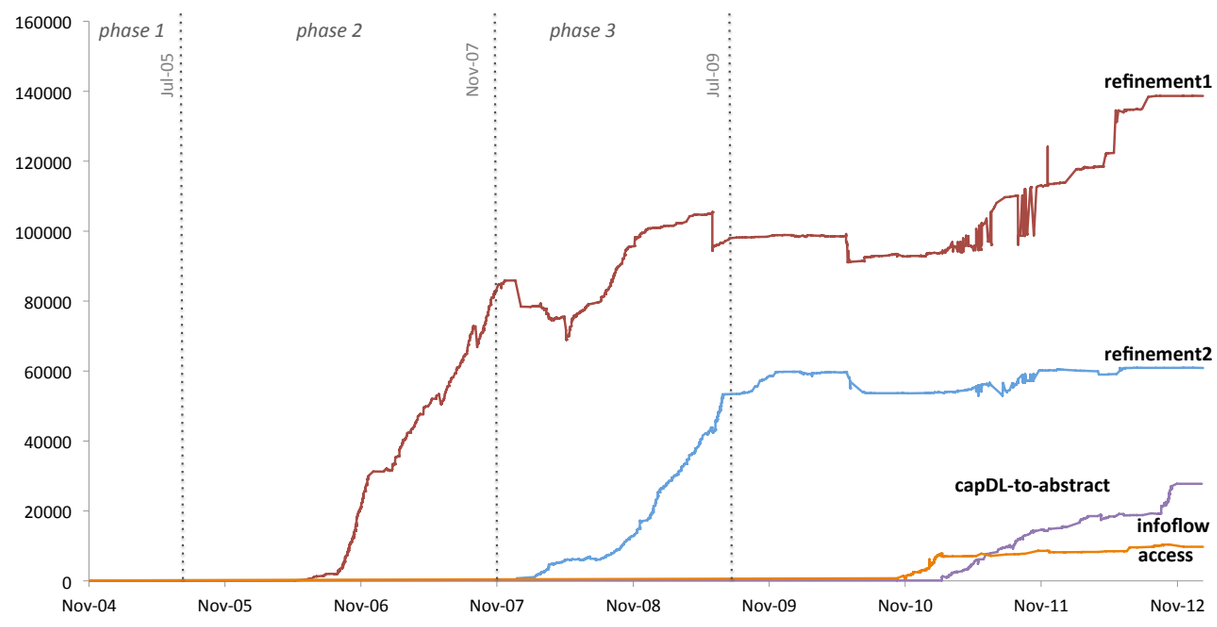

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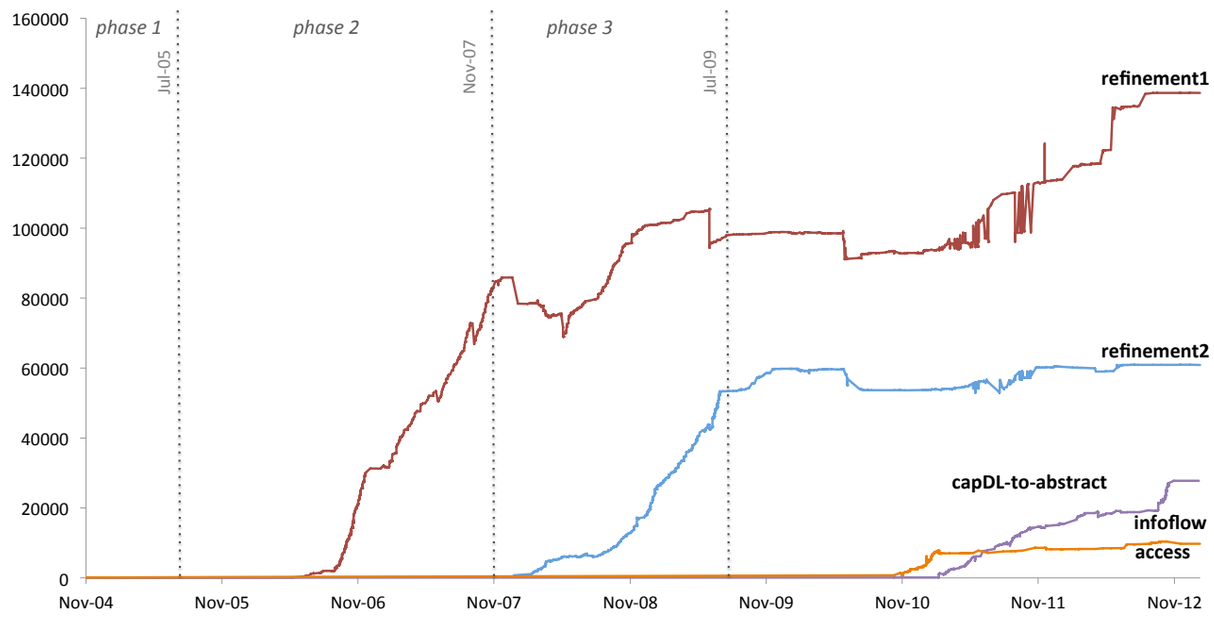
- Are they true?



Summary

seL4

- Full verification. Full performance.
- Already cost effective for high assurance.
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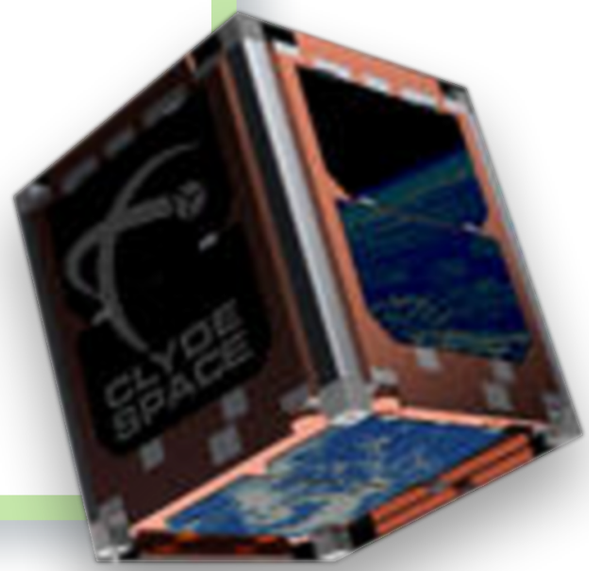

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NICTA

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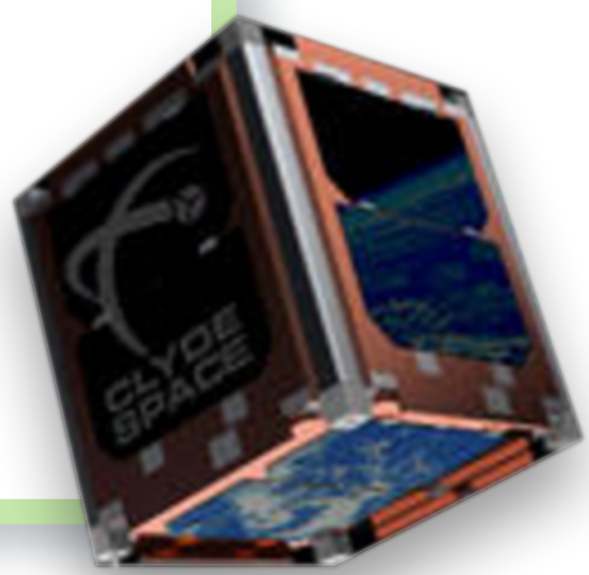
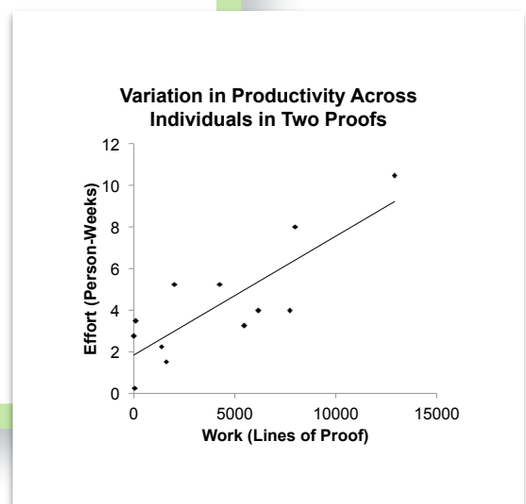


Proof Engineering

- Should become a research discipline.
- Work has started. A lot more to be done.



http://sel4.systems

From imagination to impact