Verifying security invariants in *ExpressOS*

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Mobiles devices are powerful

citibank

Gmail
by Google

PayPal™

Security of mobile devices is important

- High value targets on mobile devices

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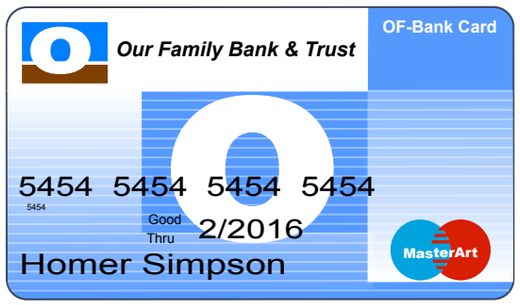

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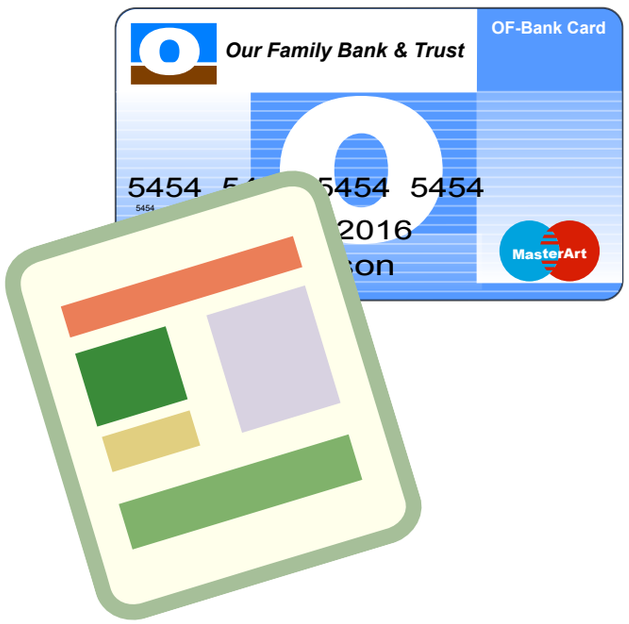

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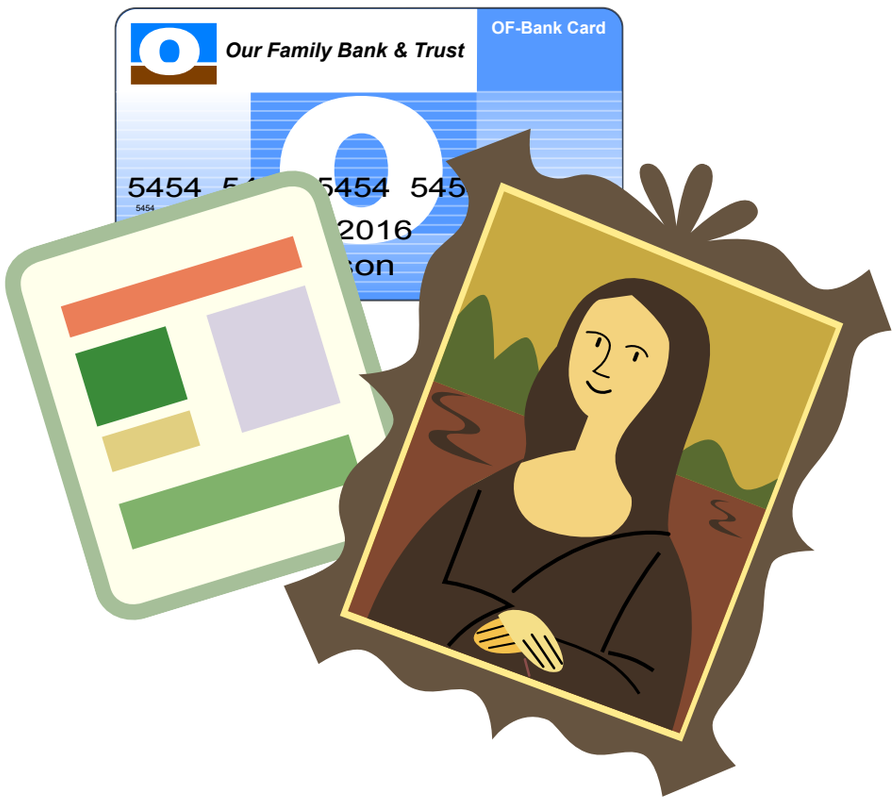

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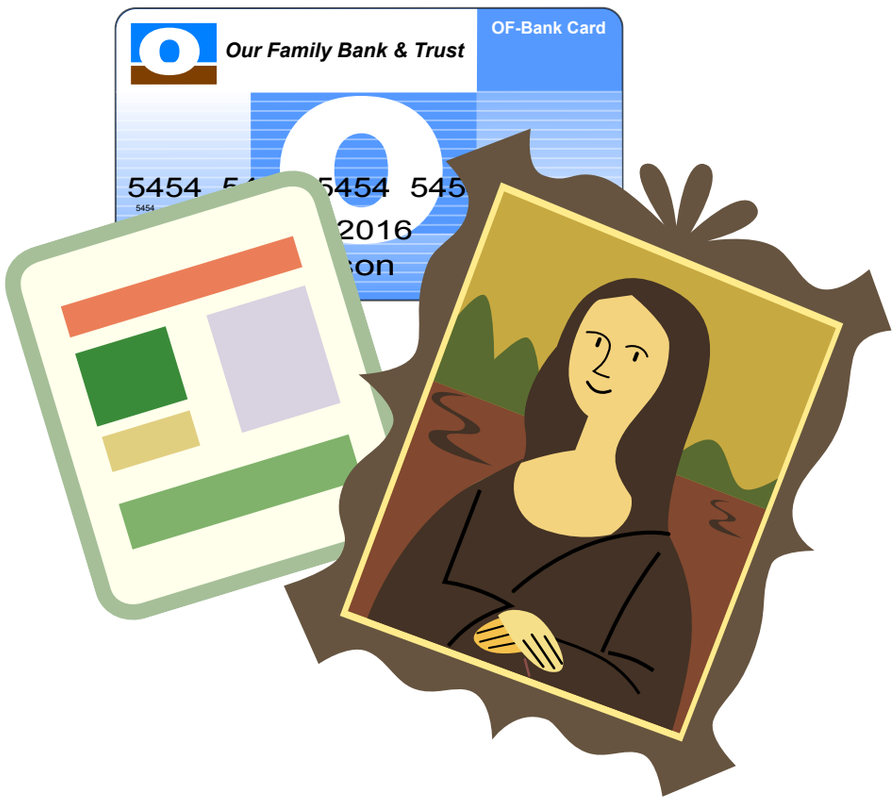

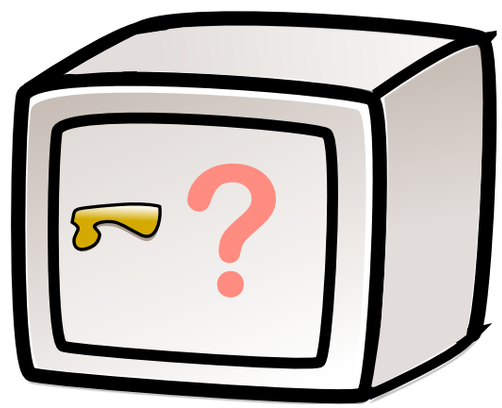

Motivating example

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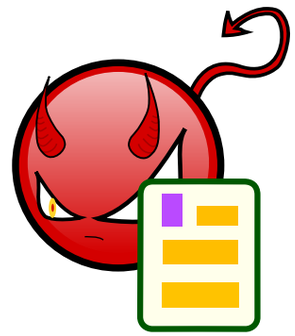
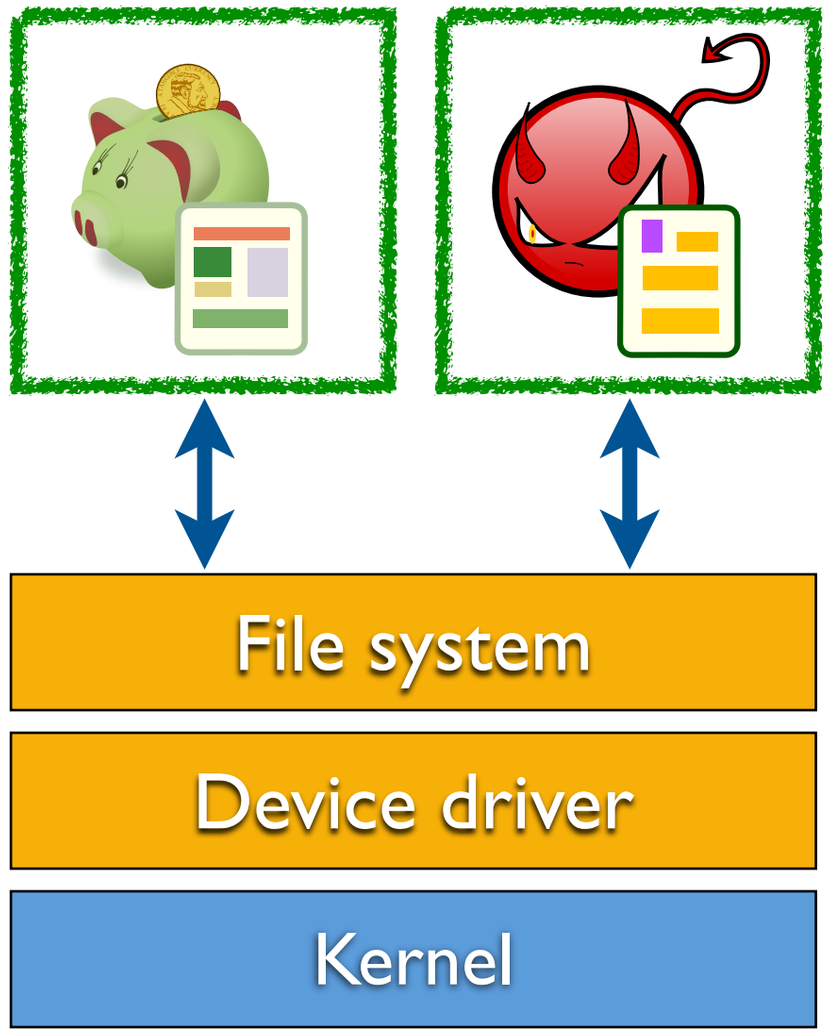


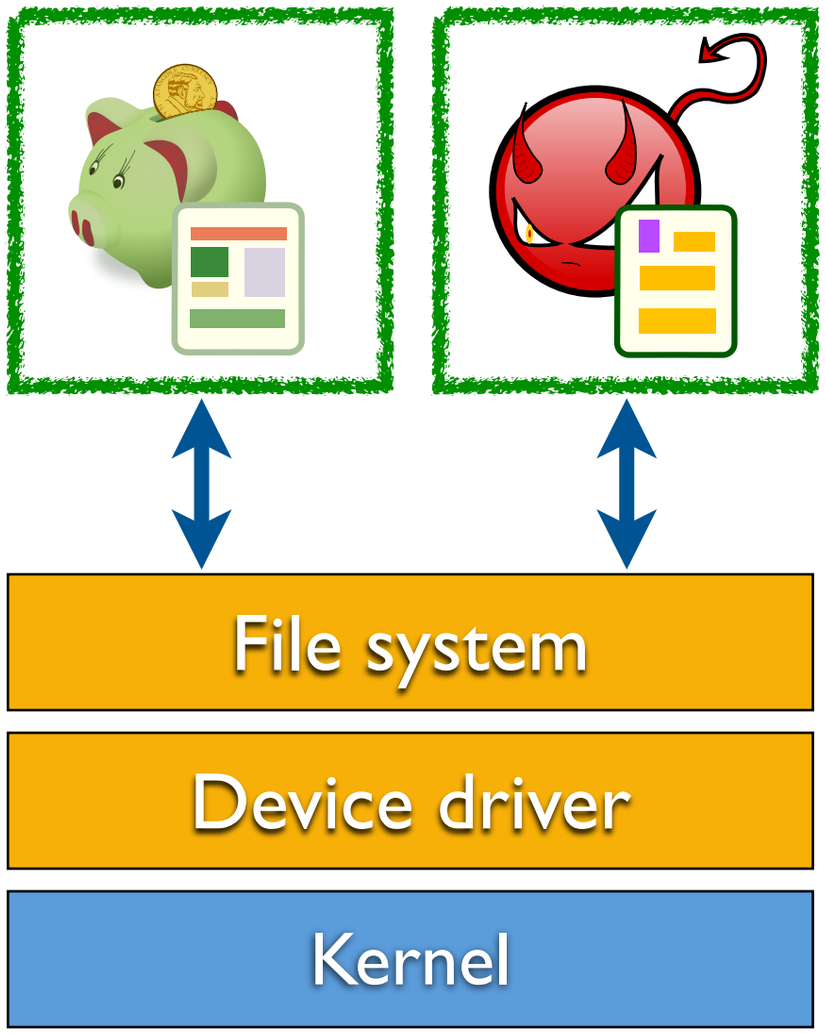
Motivating example

- Isolate the application's persistent storage from
  - other applications
  - components of the system



Motivating example

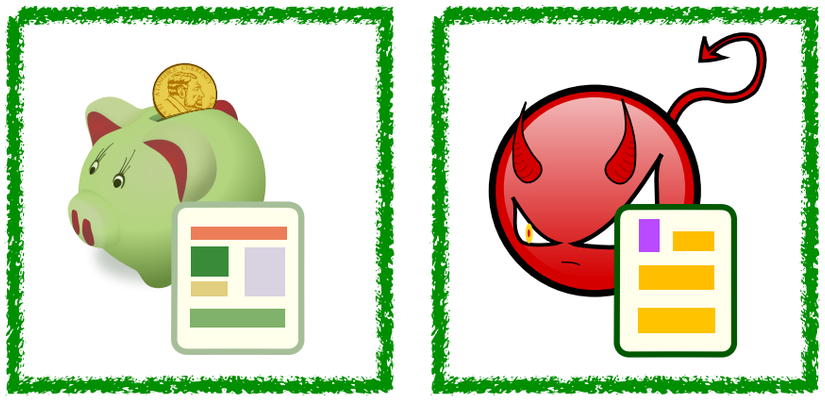
- Isolate the application's persistent storage from
  - other applications
  - components of the system
- Immediately meaningful




ROOTED


09:44
86 %
JailbreakMe by comex (et al.)
Jailbreak to get tweaks and apps Apple won't allow in the App Store.
Free, legal, safe.
You should sync with iTunes before using this tool.
More Info »
slide to jailbreak

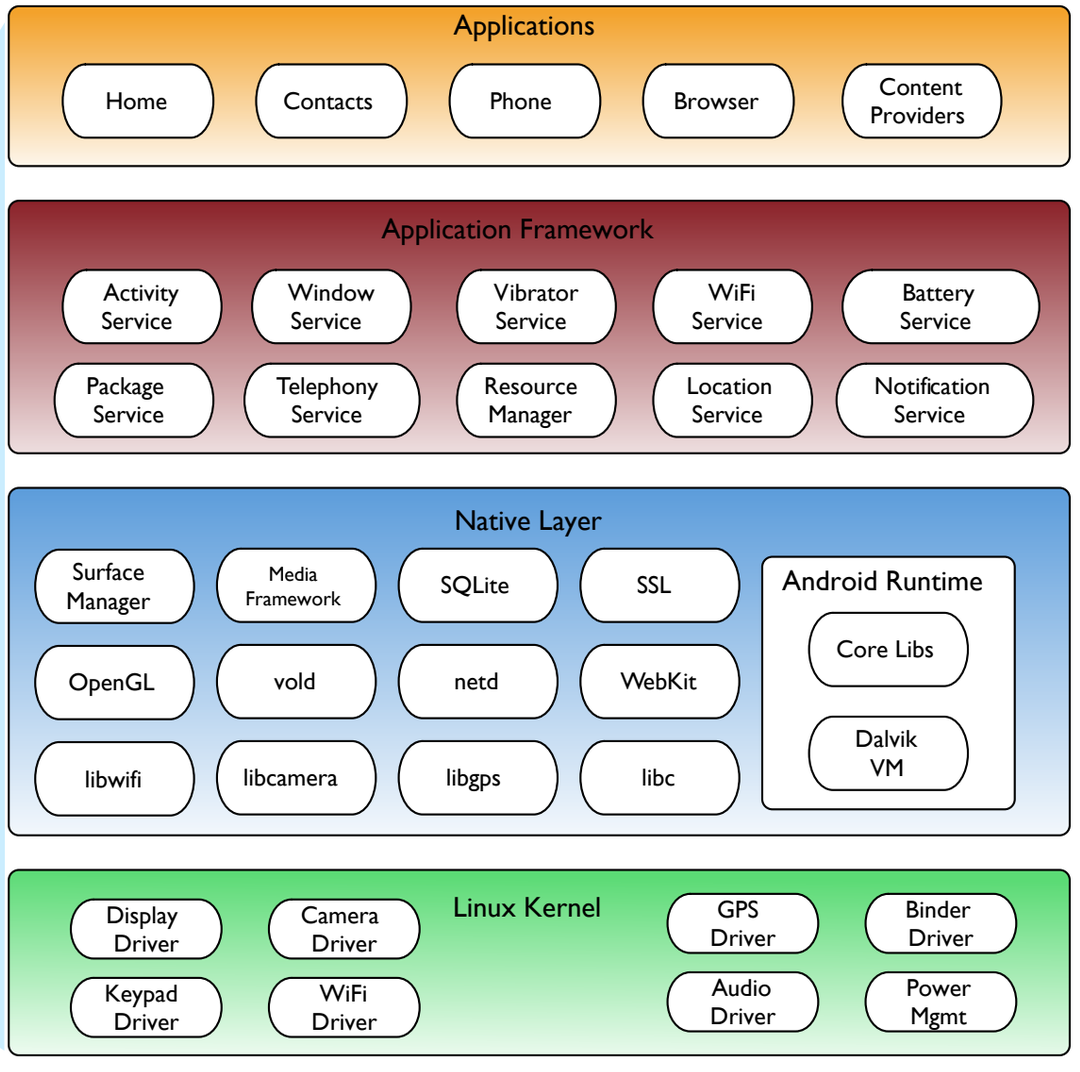
Wide attack surfaces



File system

Device driver

Kernel



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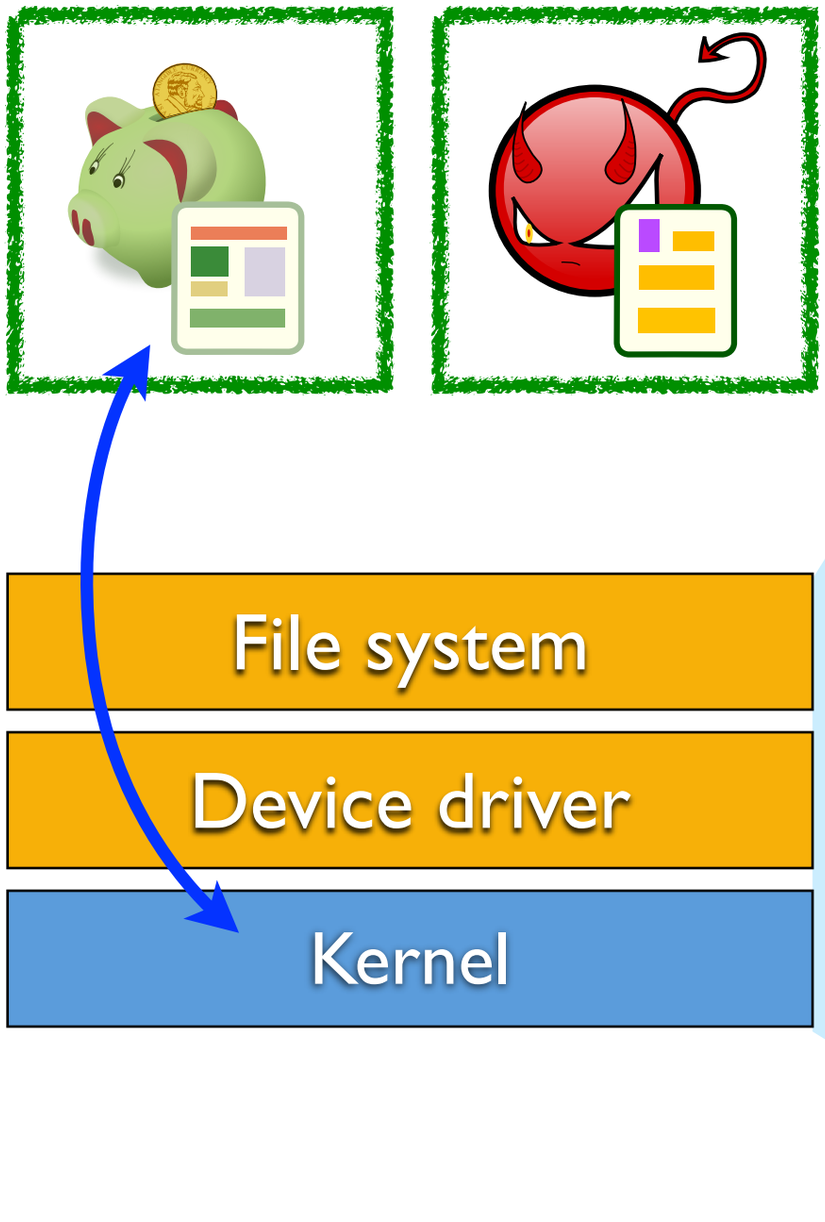

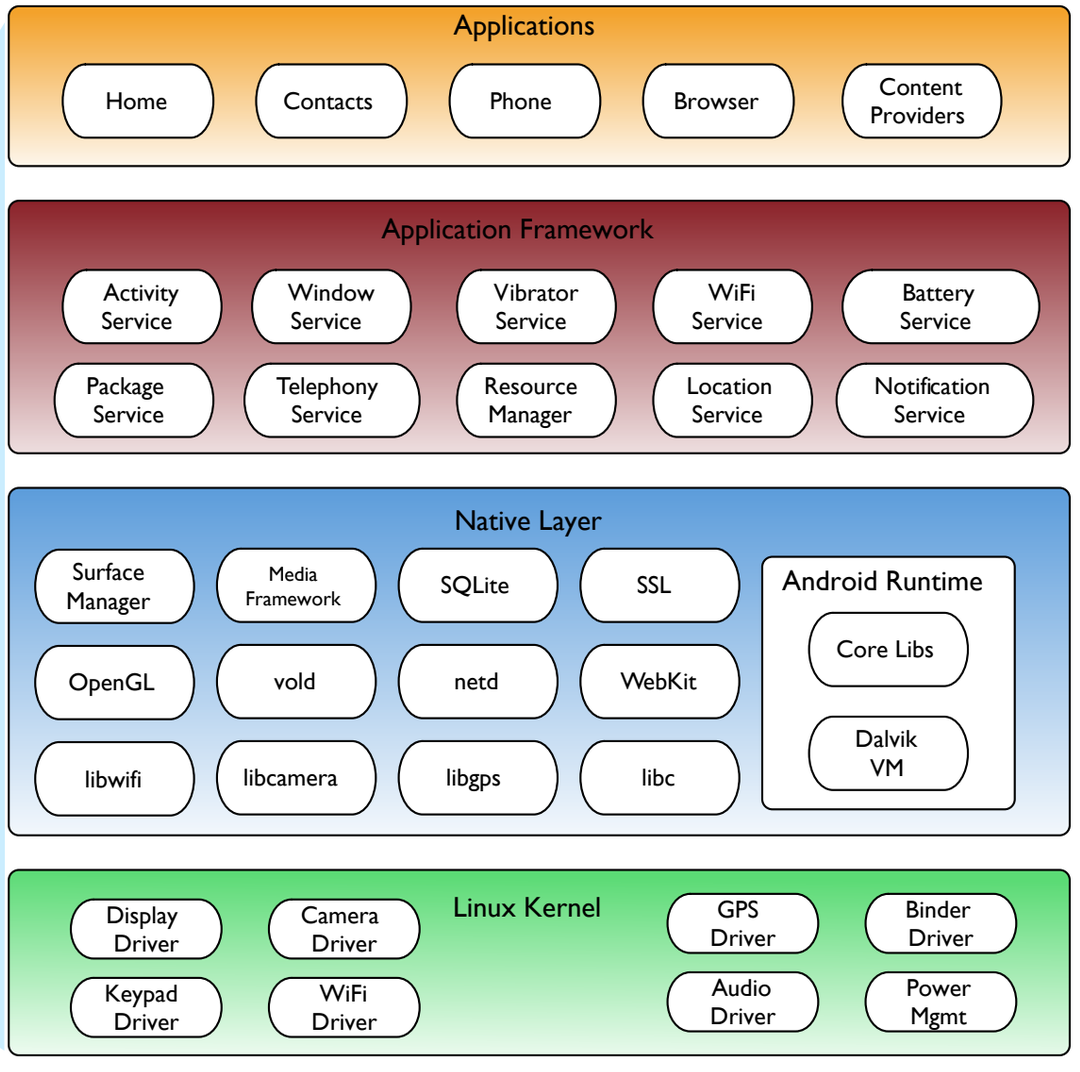

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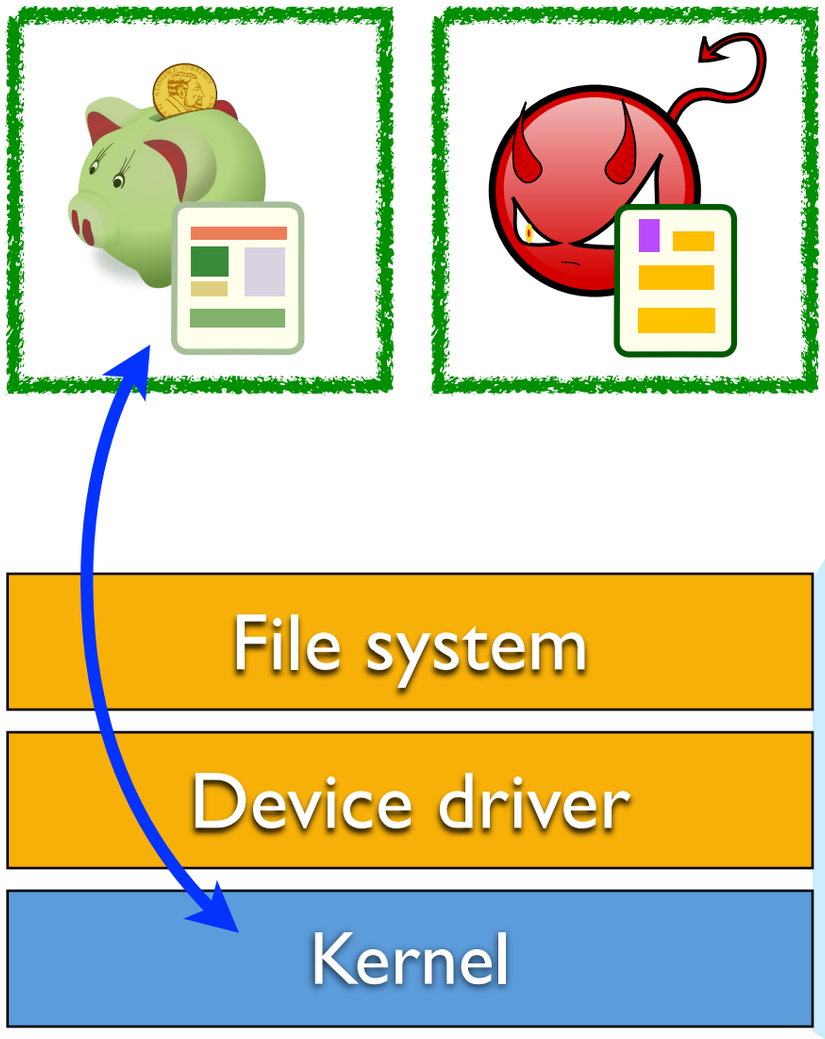

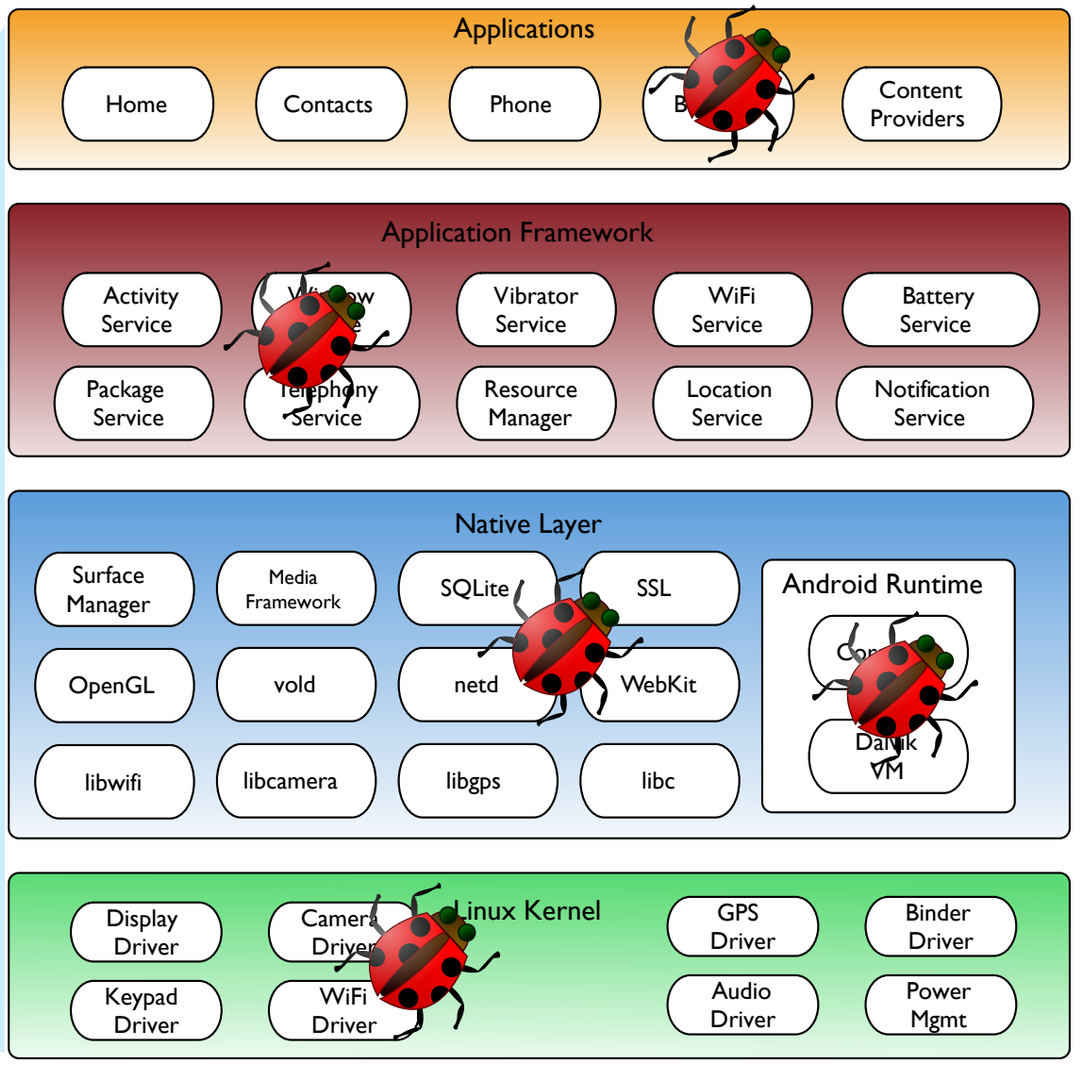

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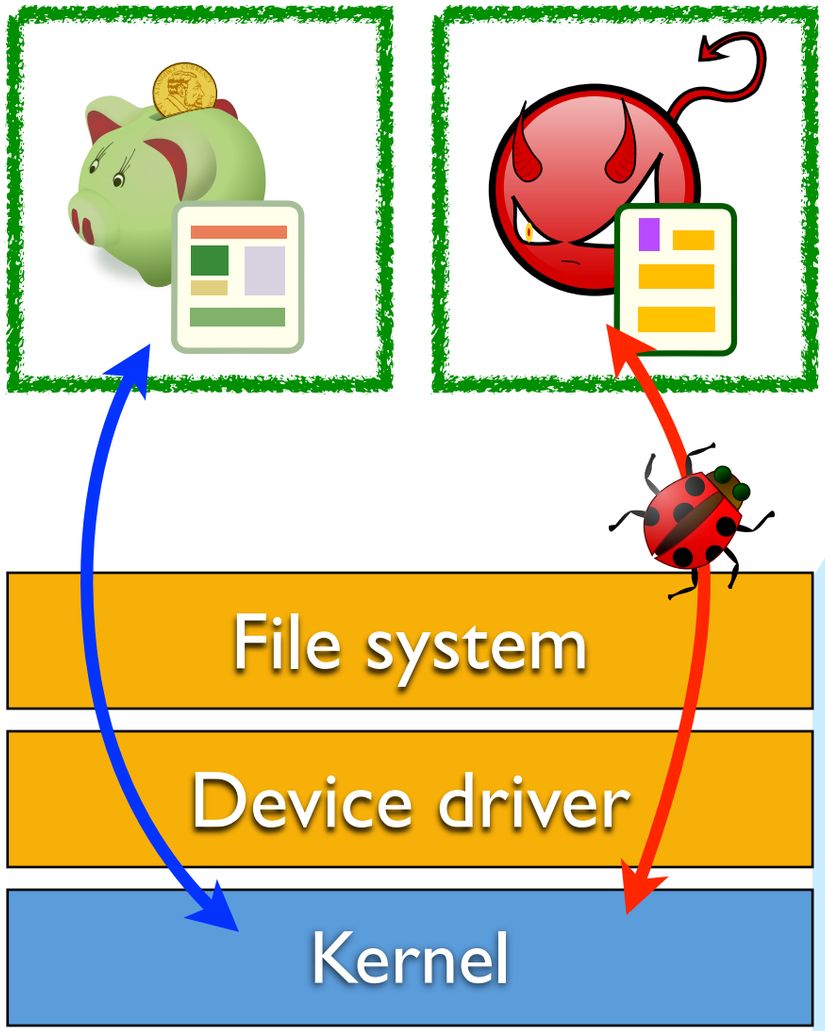

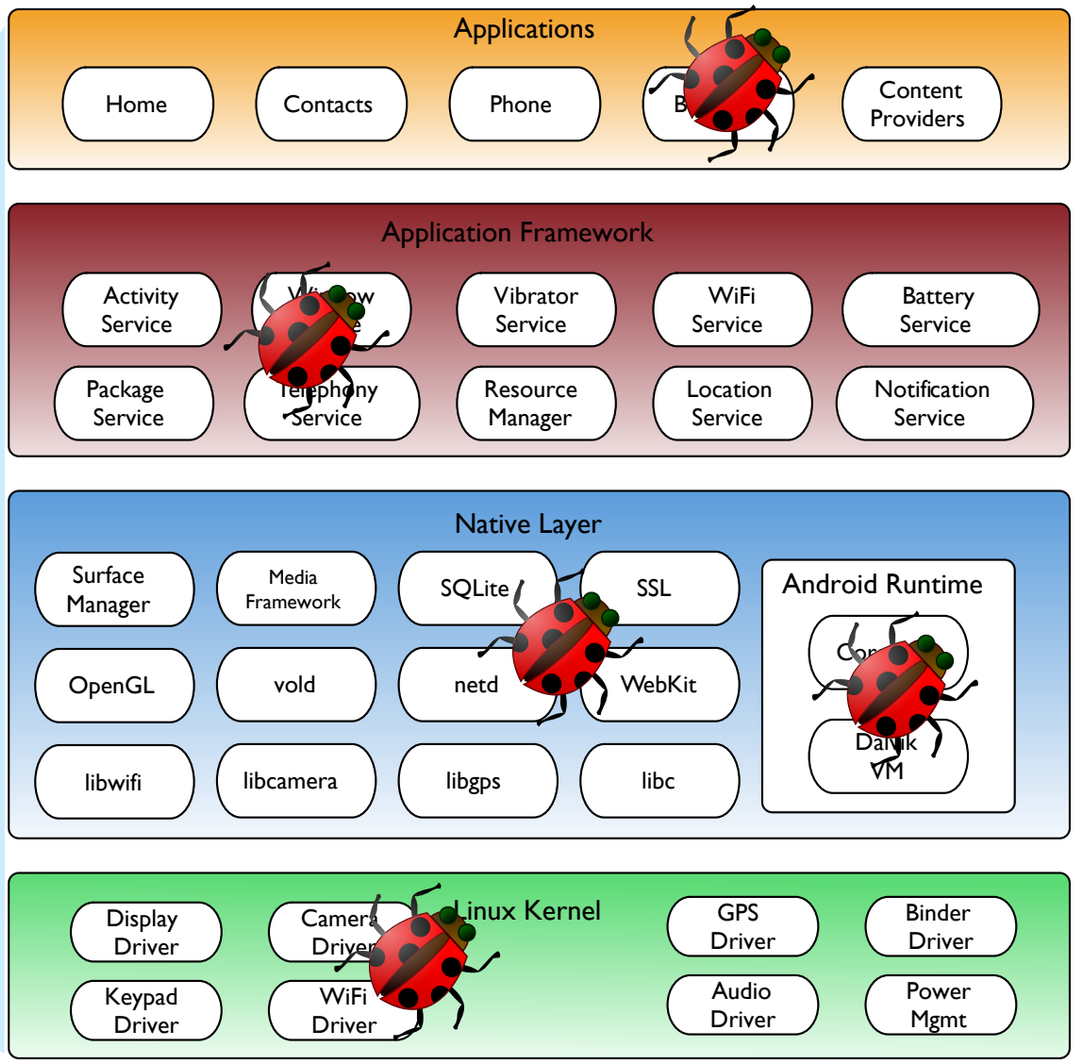

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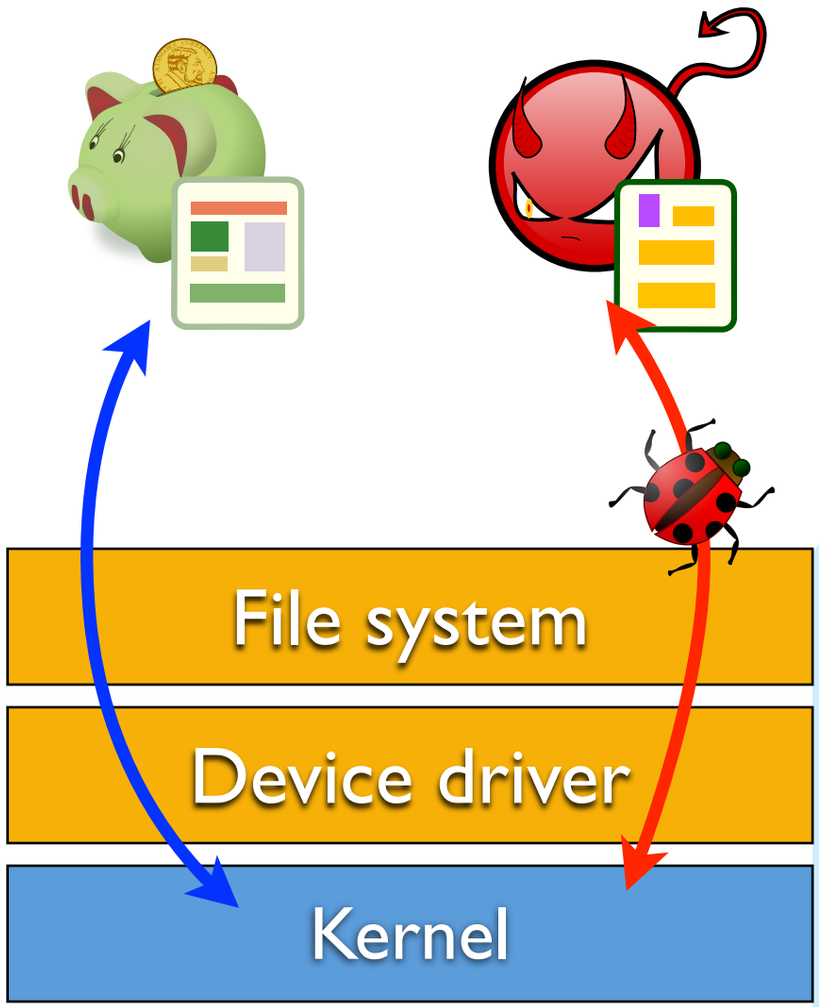
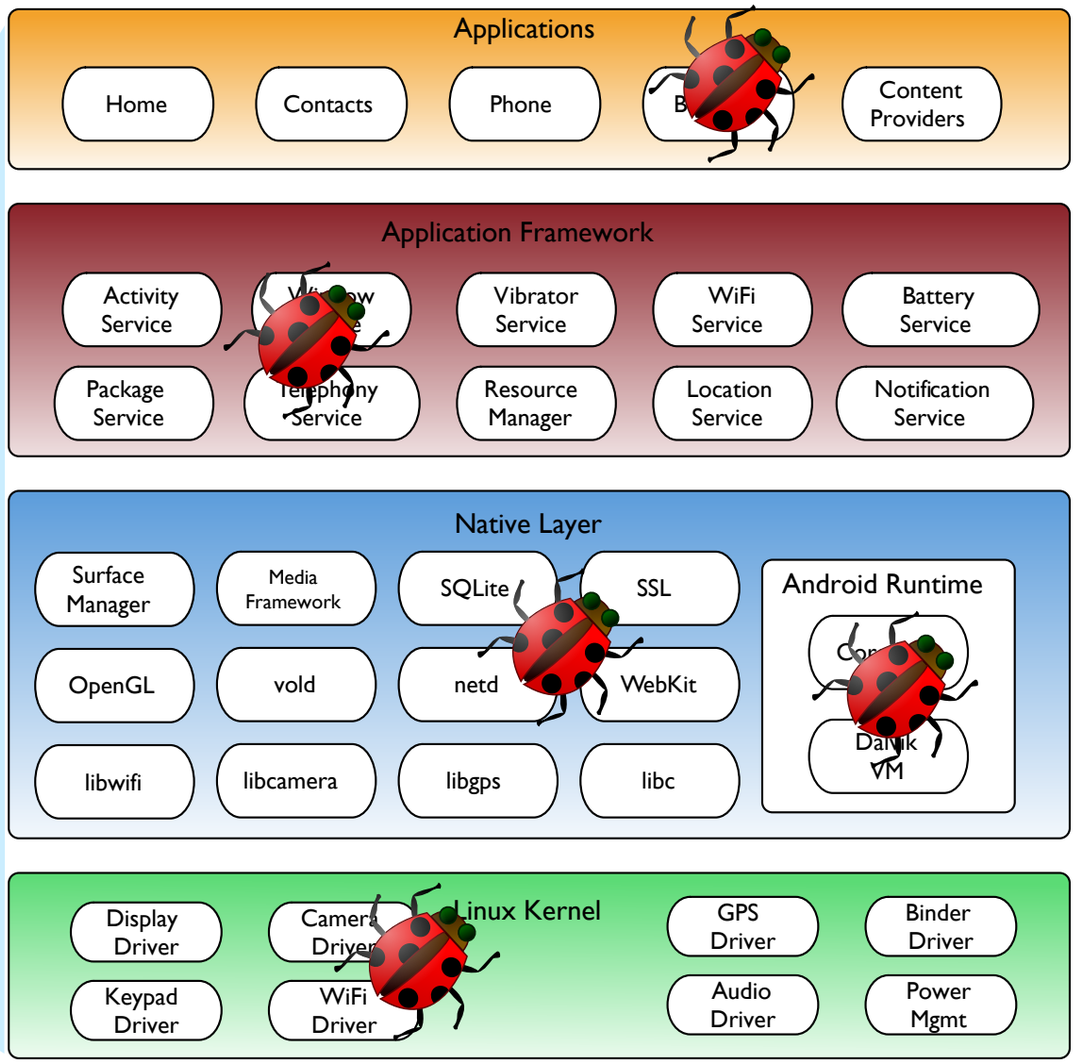
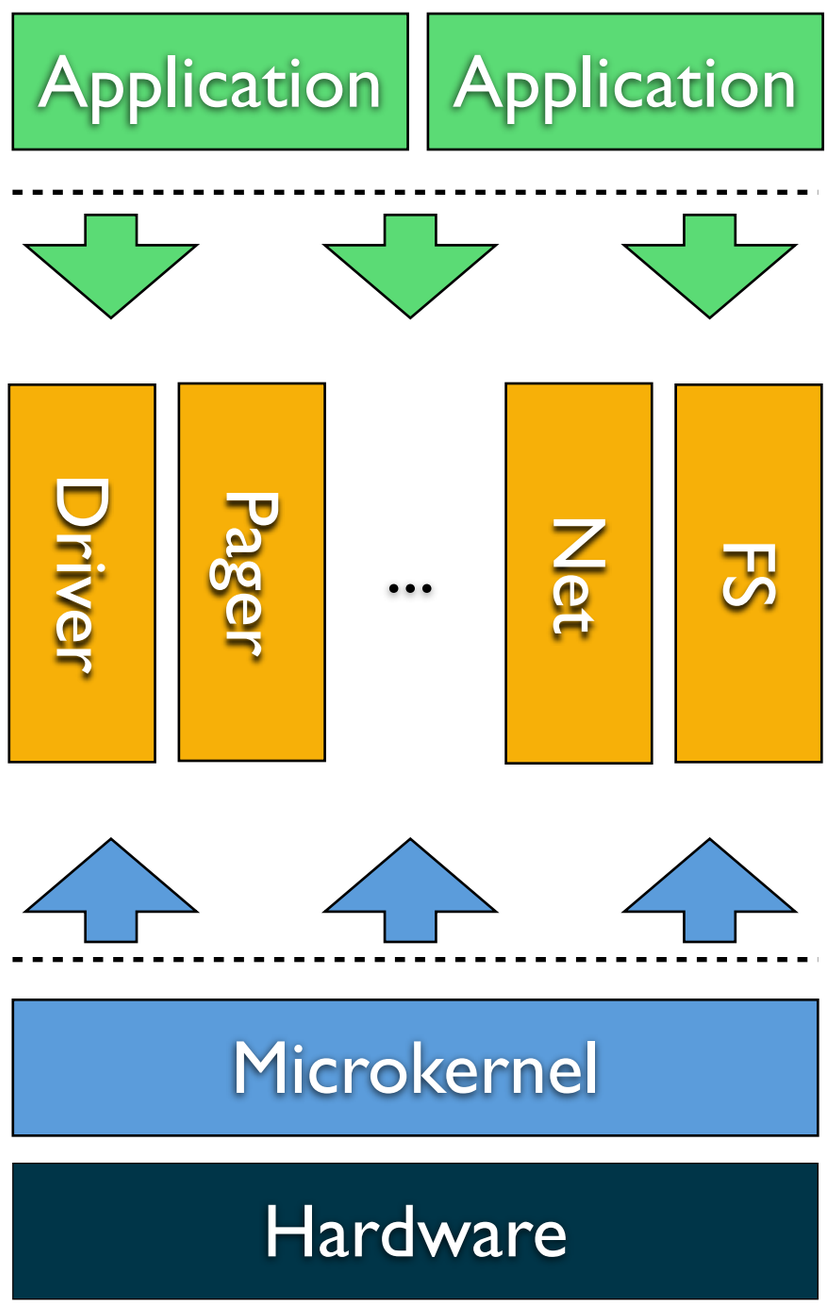


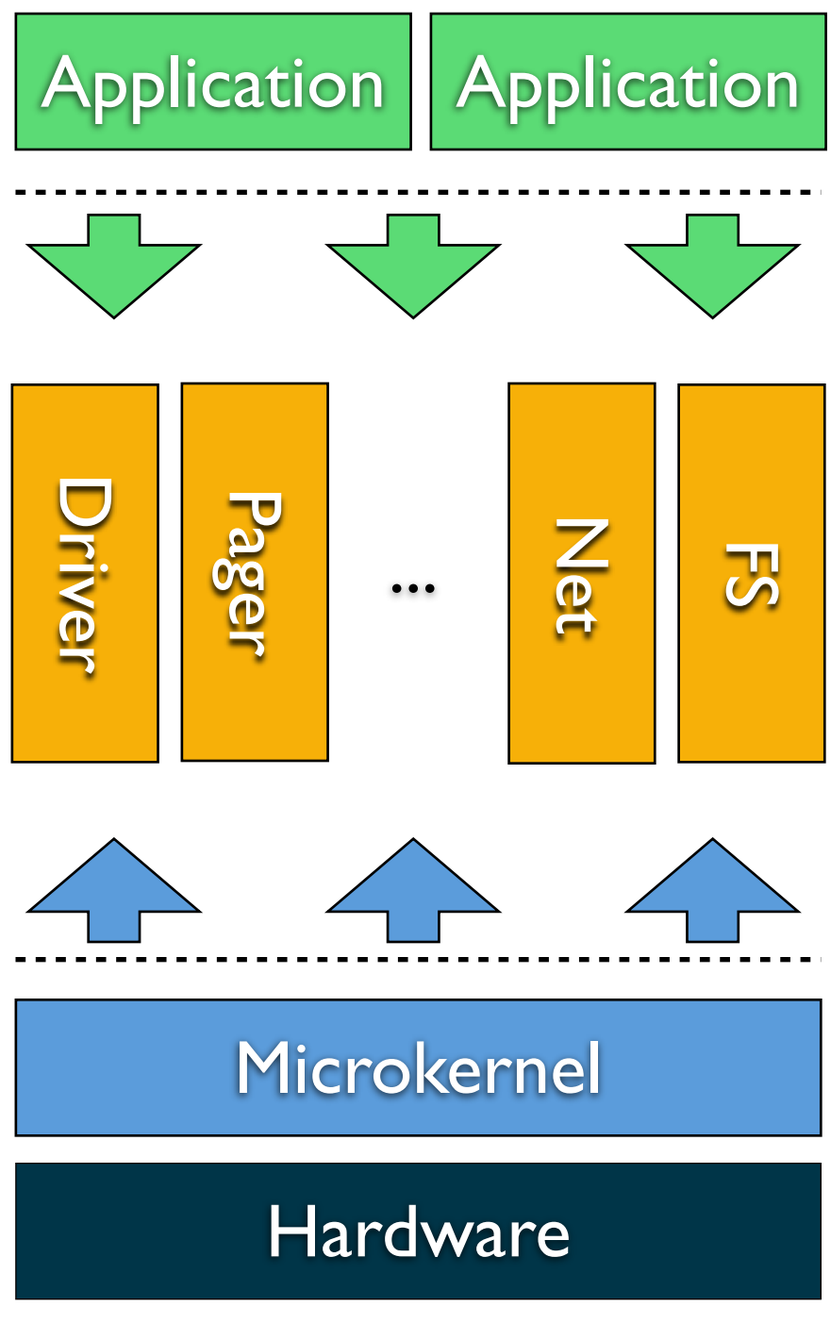


Microkernel is not enough



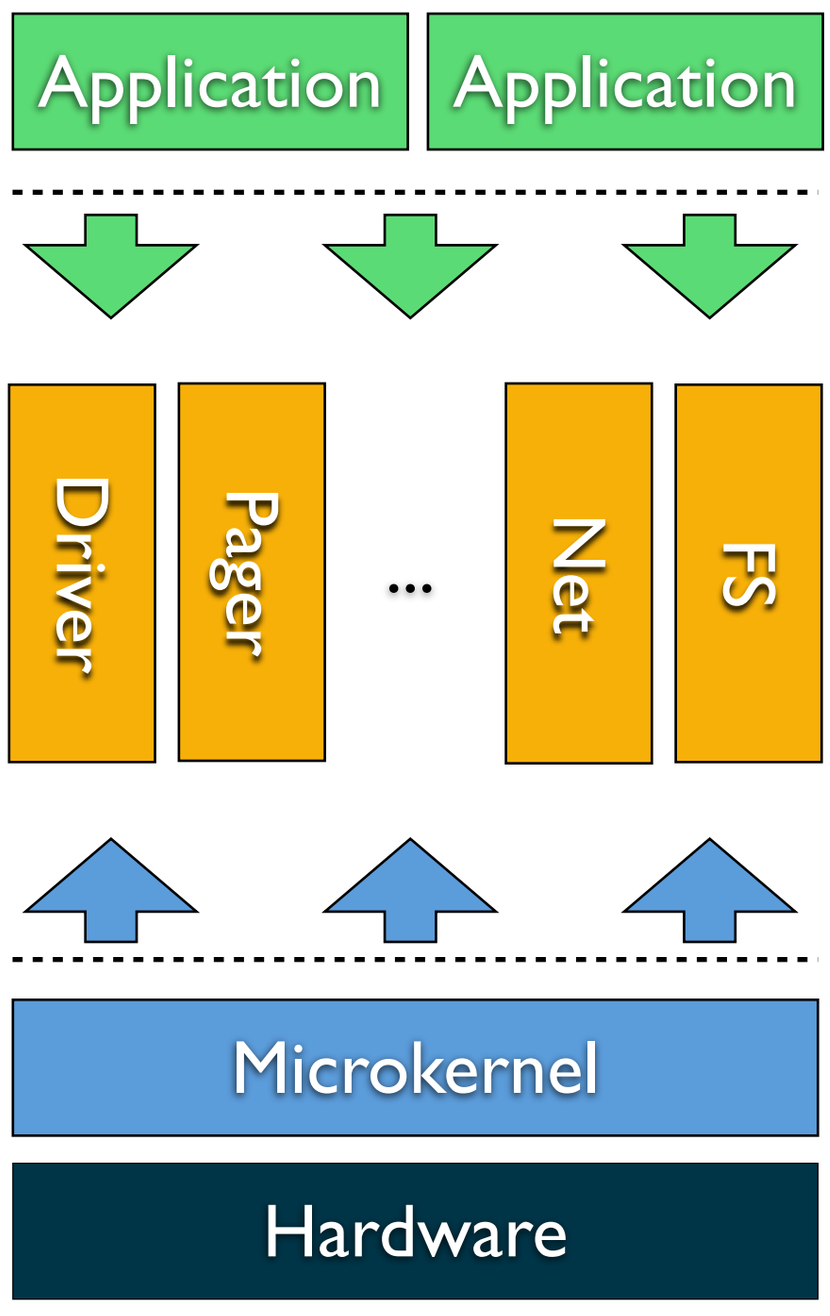
Microkernel is not enough

- Low-level abstractions
- v.s. application semantics



Microkernel is not enough

- Low-level abstractions
  - v.s. application semantics
- Shared services



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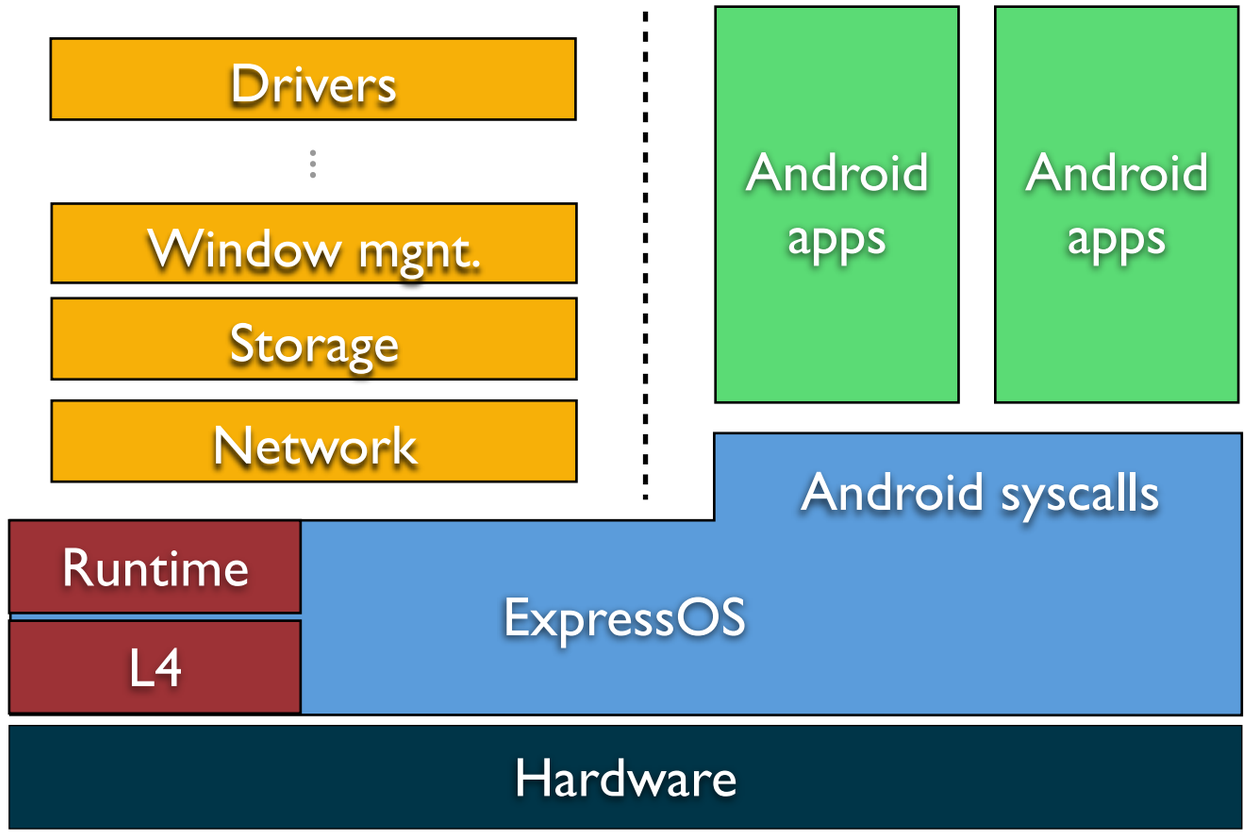
- Capture application-level security requirements as *security invariants*
- Verify security invariants *directly*
  - *NOT* from full functional correctness
- Formally verified security guarantees with *reasonable* verification effort

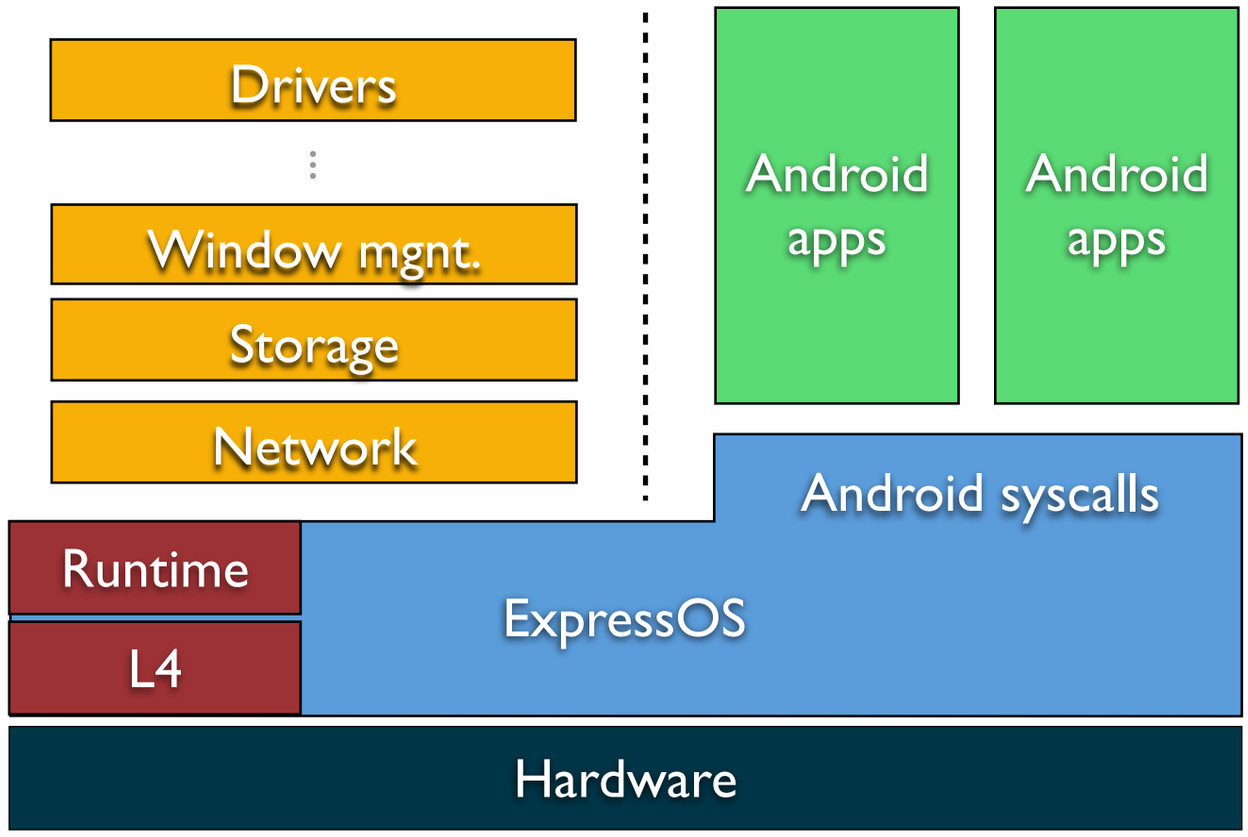
- Introduction
- Verifying security invariants
- Experience
- Conclusion

Design tailored for verification



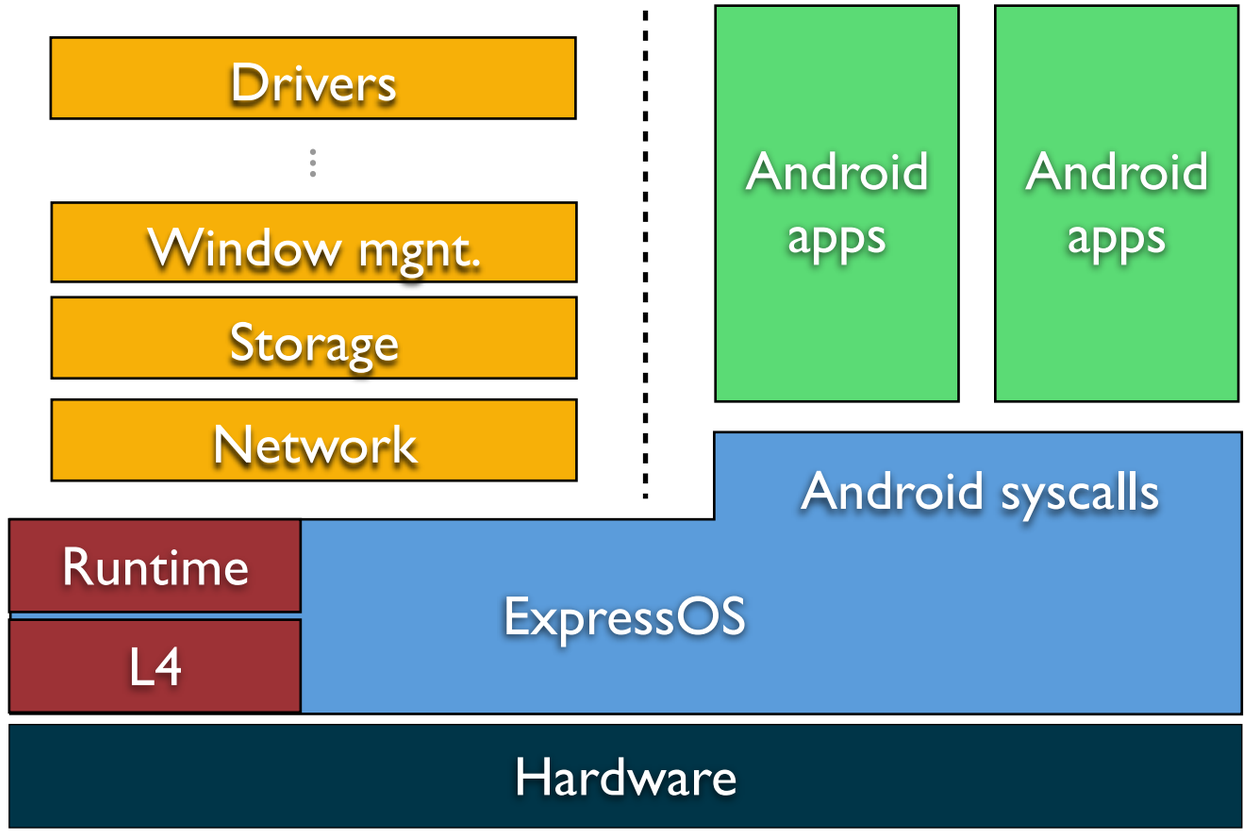
Design tailored for verification

- Understand application semantics
  - Provides Android/Linux-like syscalls

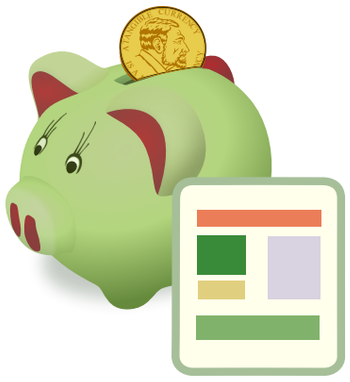


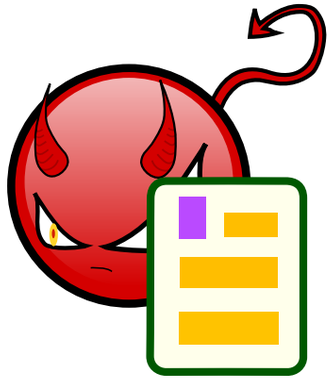
Design tailored for verification

- Understand application semantics
  - Provides Android/Linux-like syscalls
- Bugs in unverified components cannot subvert the security invariants
  - Microkernel
  - Type safety (C# + Dafny)



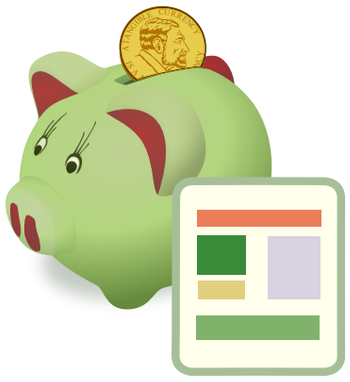
Security invariants

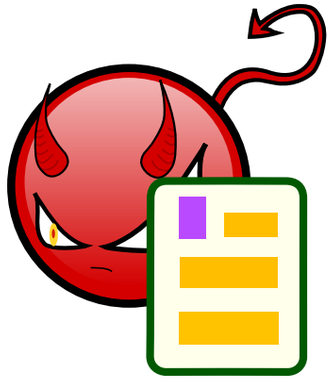




- Secure storage
- Memory isolation
- UI isolation
- Secure IPC

Security invariants





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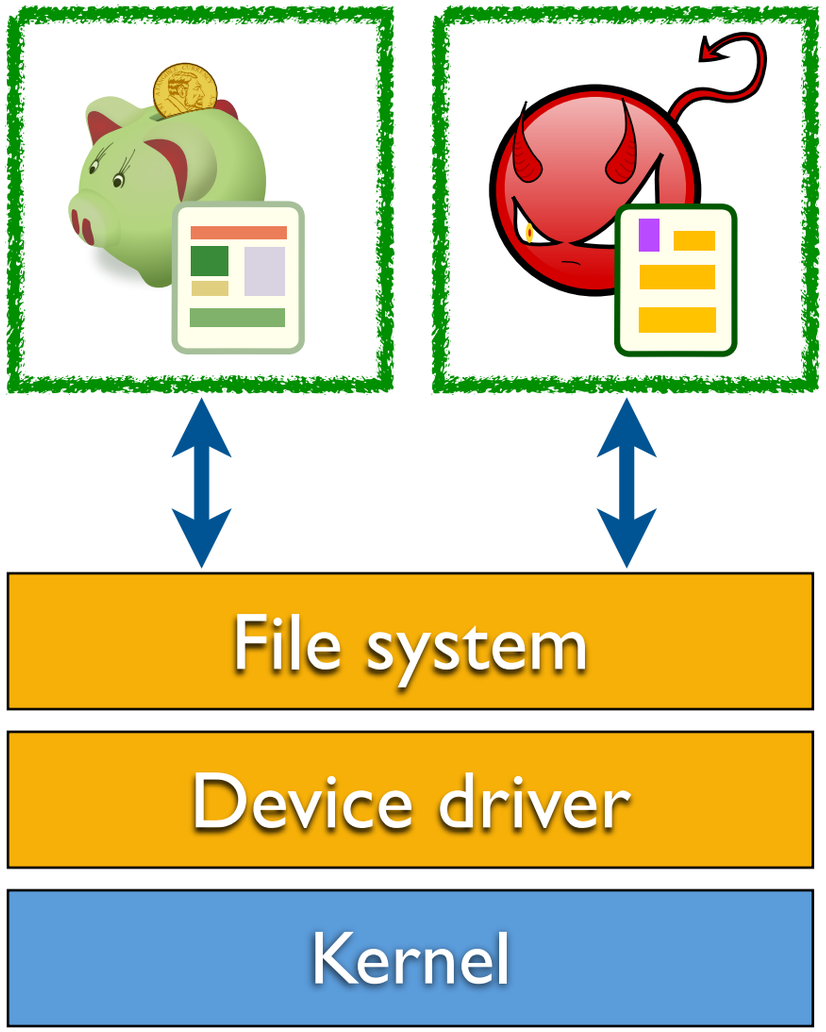
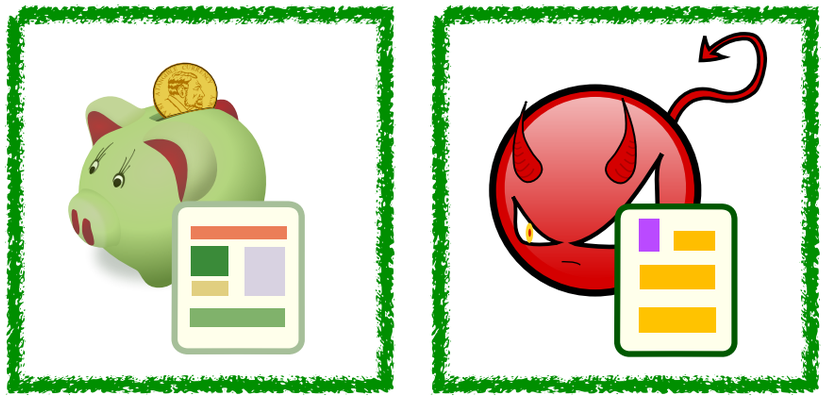
Secure storage

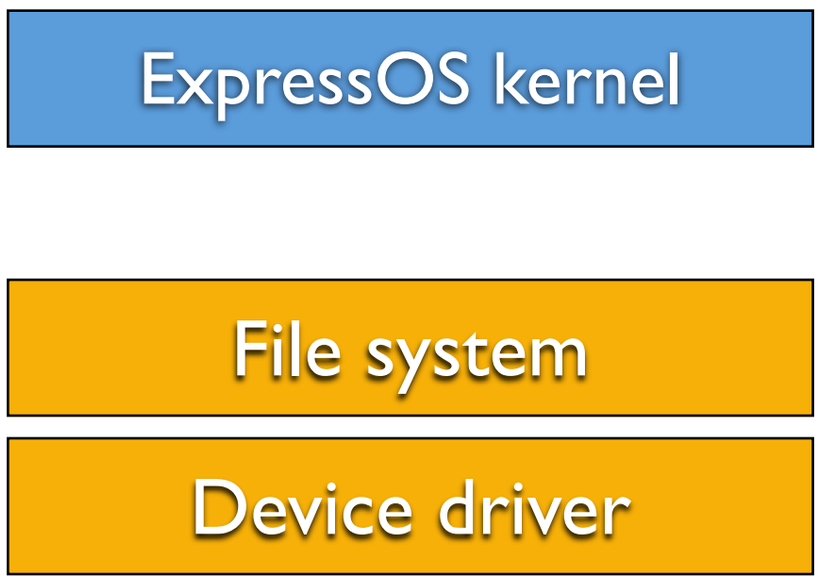
- The persistent storage of an application should be isolated from other applications and the system



Secure storage

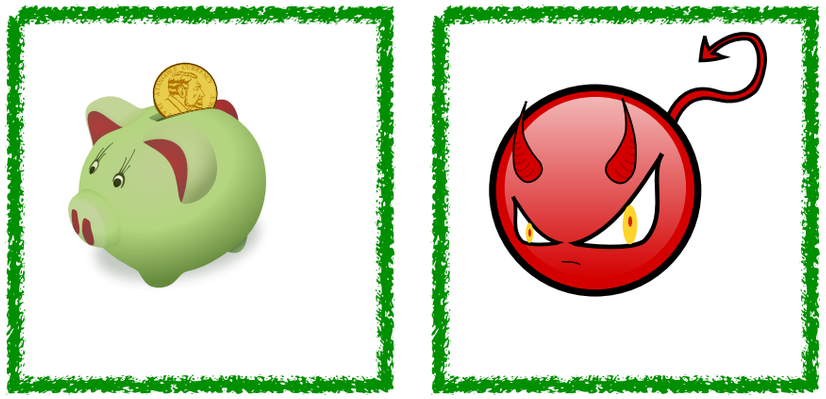
- ExpressOS kernel provides file APIs to applications





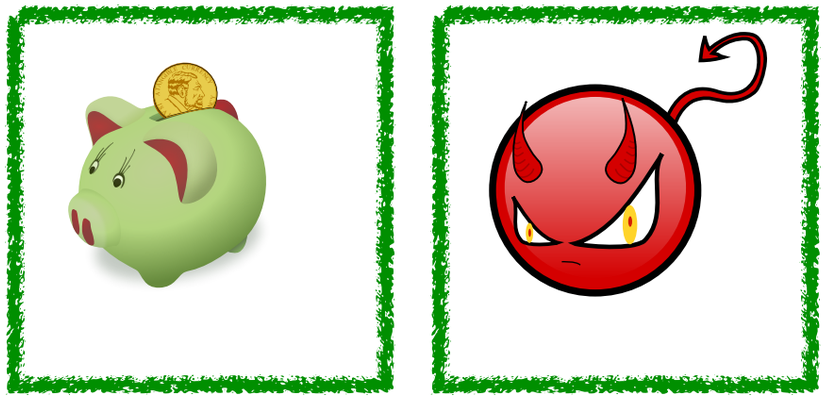
Secure storage

- ExpressOS kernel provides file APIs to applications
- Enforce confidentiality and integrity using HMAC and encryption
- *Verify* these primitives are used correctly



Secure storage

- ExpressOS kernel provides file APIs to applications
- Enforce confidentiality and integrity using HMAC and encryption
- *Verify* these primitives are used correctly
- No trusts on FS / drivers



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- L4 and the language run-time
- Correct specifications

- Do not cover covert channels

Tools for verification

Tools for verification

	Code Contracts	Dafny
Power	*Restricted* (abstract interpretation)	*Expressive* (SMT solvers like Z3)
Annota-tion burden	*Low* (~0.01 lines per LOC)	*High* (5~6 lines per LOC)

Tools for verification

- Dafny only

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- Code contract(CC) only

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Tools for verification

- Dafny only

  ✗ Too much work

- Code contract(CC) only

  ✗ Incomplete

- Dafny + code contracts

  ✓ Practical

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Example of code contracts

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class Foo {
  int m;
  void Increment() {
    ++m;

  }
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Assertion
Contract.Assert(...);

Example of code contracts

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class Foo {

   int m;

   void Increment() {

      ++m;

   }

}
```

Pre-condition
Contract.Requires(m > 0);

Assertion
Contract.Assert(...);

Post-condition
Contract.Ensures(m == Contract.Old(m) + 1);

Example of Dafny

```
var Head: Foo;
void IncAll() {
  var p := Head;
  while (p != null) {
    p.Increment(); p := p.Next;
  }
}
```

Example of Dafny

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Ghost code

code for verification only

Example of Dafny

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var Head: Foo;

void IncAll() {
  var p := Head;
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  }
}
```

ghost var C :seq<Foo>;

ghost var i := 0;

invariant C[i] == p ∧
p.Next == C[i+1];....

i := i + 1;

assert ∀x, x∈C → x ≠ null ∧
x.m == old(x.m) + 1;

Ghost code

code for verification only

Checking that all data is encrypted using ghost variables

```
class FilePage {

enum State { Empty,
Authentic, Decrypted,
Encrypted }

[Ghost] State S;


void Decrypt(...) {
  Contract.Requires(S ==
State.Authentic);
  Contract.Ensures(S ==
State.Decrypted); ...

}

...
```

Checking that all data is encrypted using ghost variables

- Ghost variable S records the state of the page
- Parts of the specification

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Checking that all data is encrypted using ghost variables

- Ghost variable S records the state of the page
  - Parts of the specification
- Pre-/post-conditions model the state transitions

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class FilePage {

enum State { Empty,
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[Ghost] State S;


void Decrypt(...) {
  Contract.Requires(S ==
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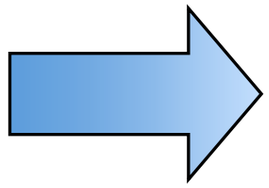
}

...
```

Checking that all data is encrypted using ghost variables

- Encrypt *all* data before sending it to FS / drivers



```
class FilePage {

...

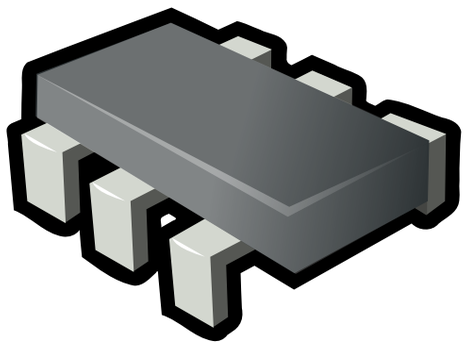
  void Flush(...) {
    Contract.Requires(S ==
State.Encrypted);

    ...

  }

}
```

Memory isolation



- The pager can read a file and bring it into the application's memory *only if* the application has proper accesses to the file.

Challenge: asynchronous execution

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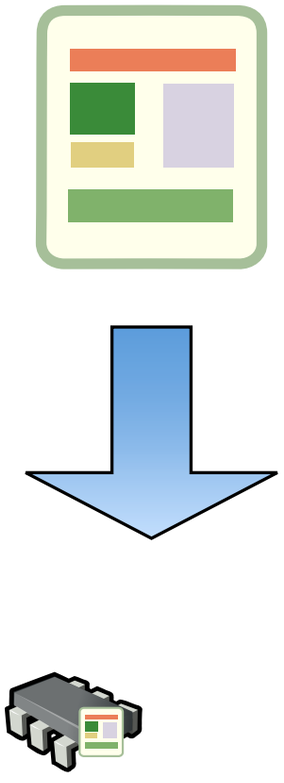
open/mmap



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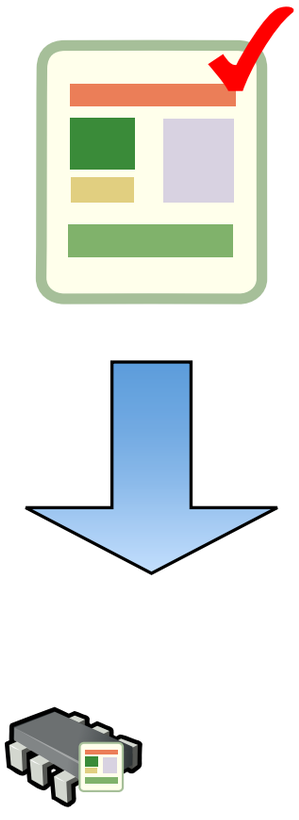

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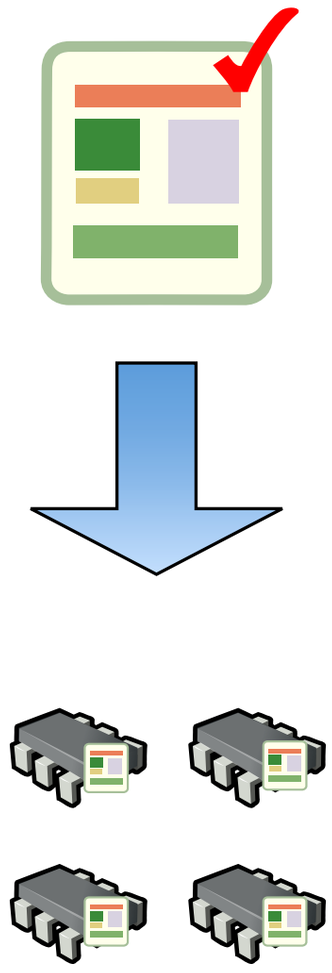

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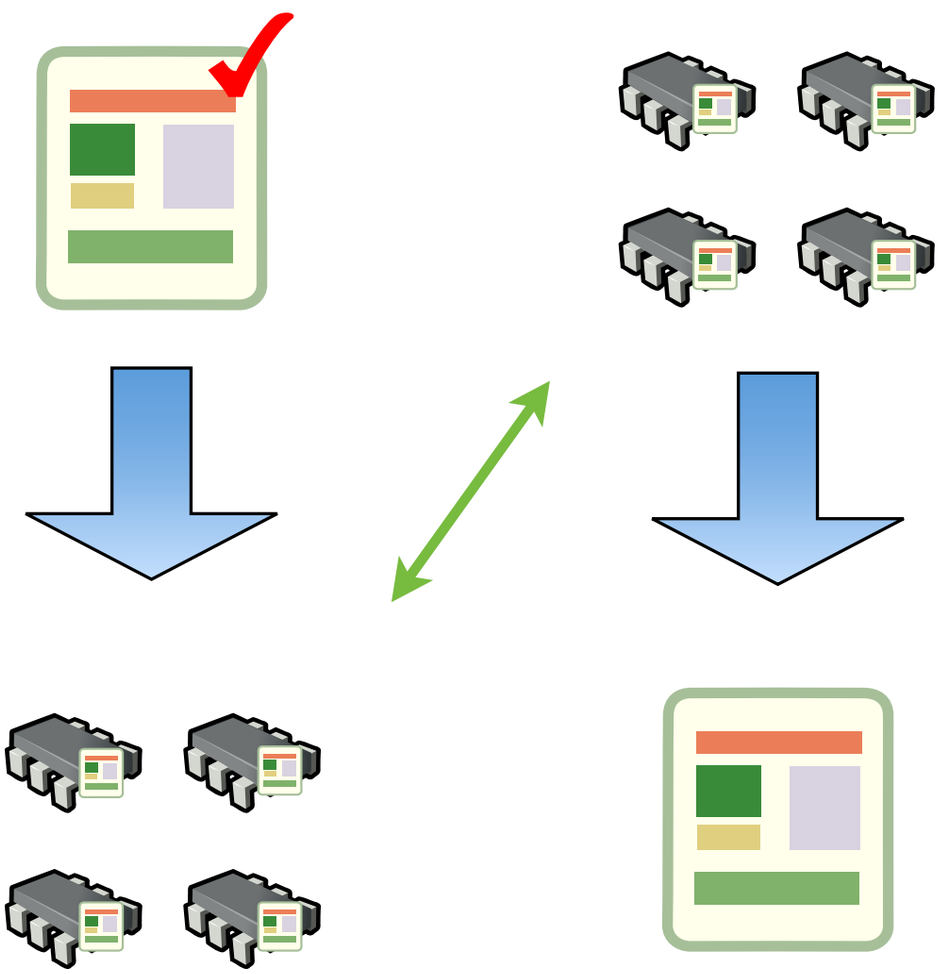
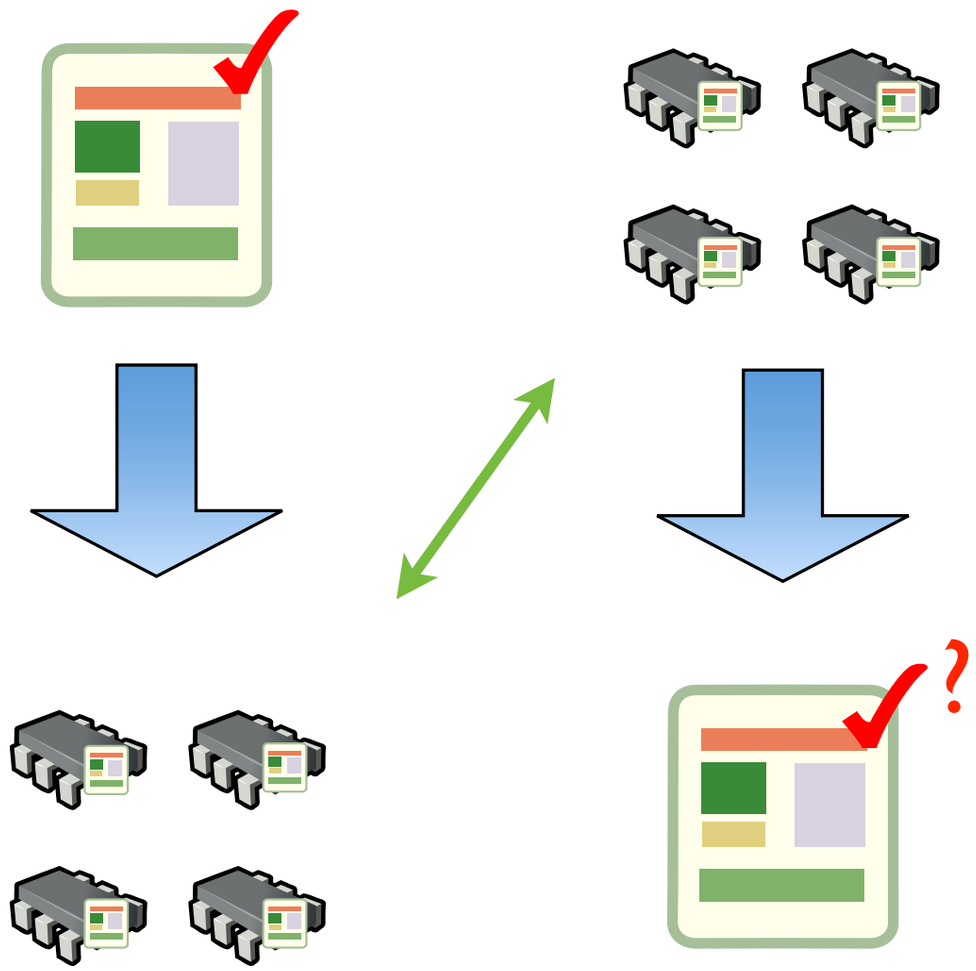


Challenge: asynchronous execution

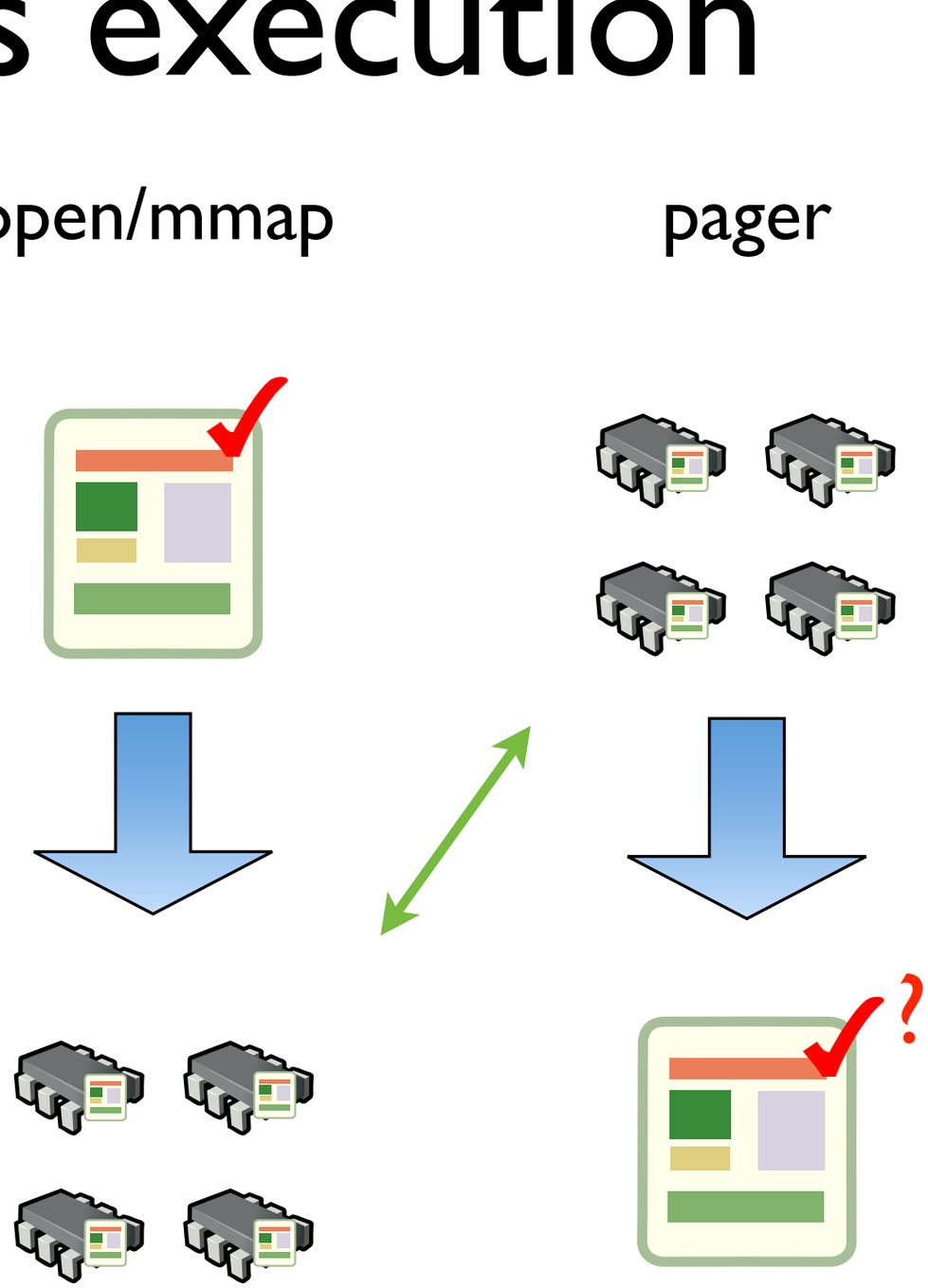
- Insufficient information at the point of assertions



Challenge: asynchronous execution

- Insufficient information at the point of assertions

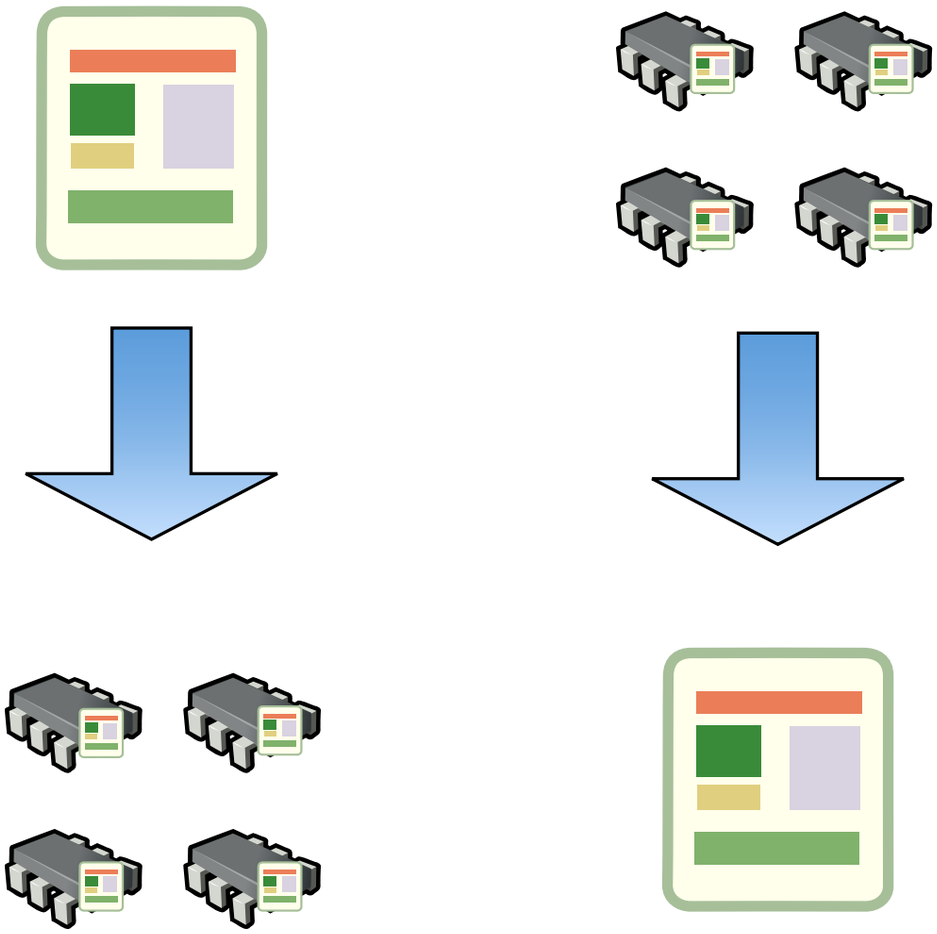
- Permission checks and paging in different execution contexts



Solution: strengthen object invariants

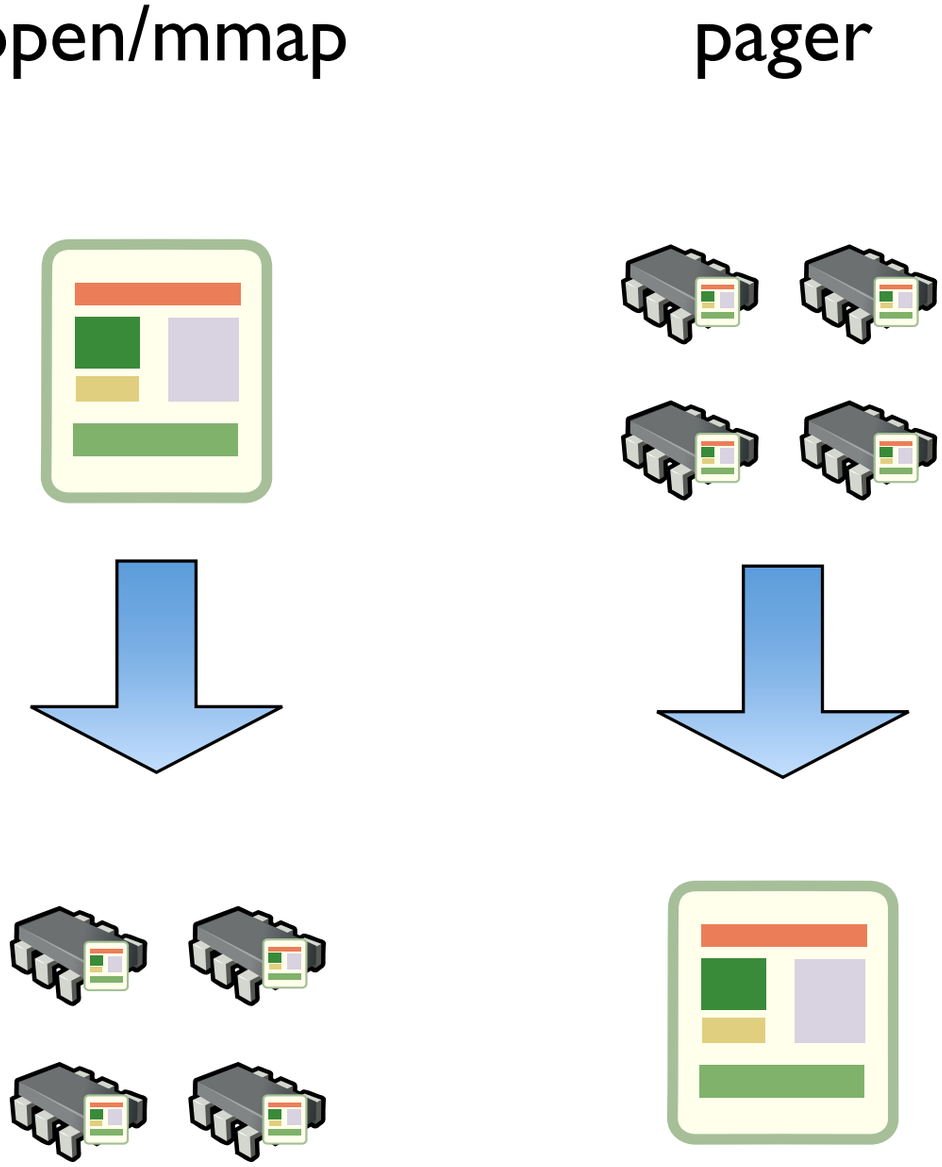
open/mmap

pager



Solution: strengthen object invariants

- Object invariants: properties *always hold* for the object



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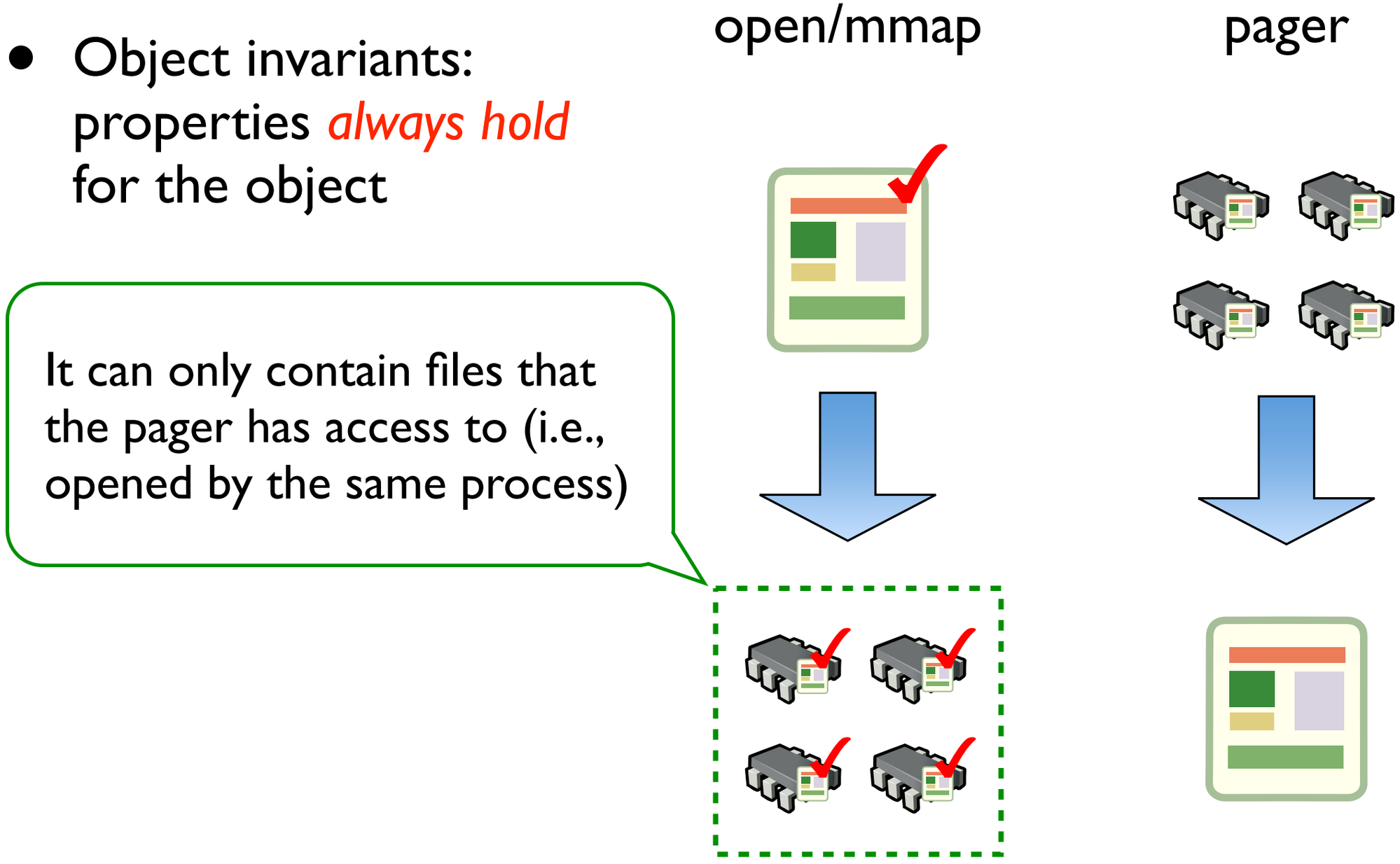

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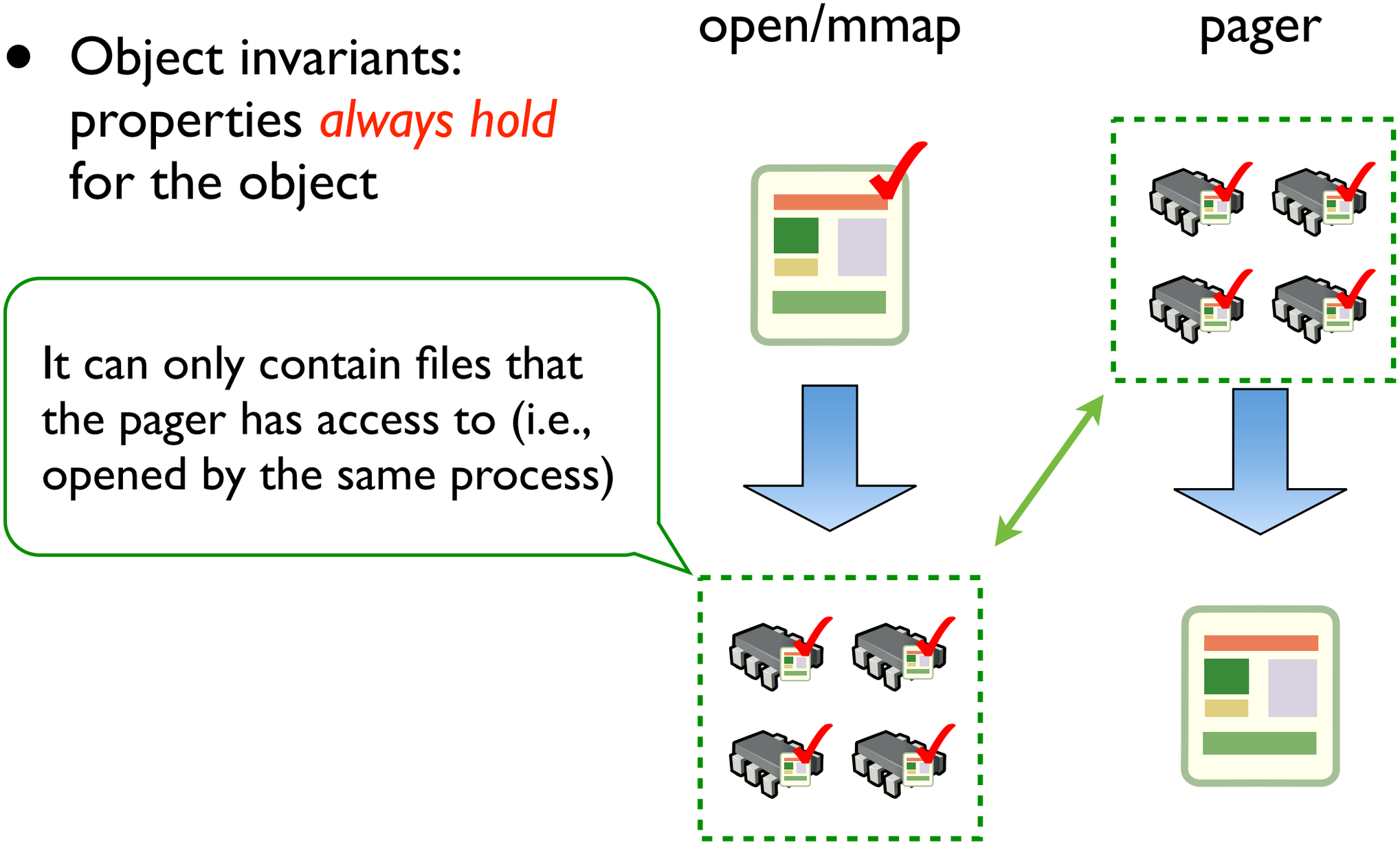
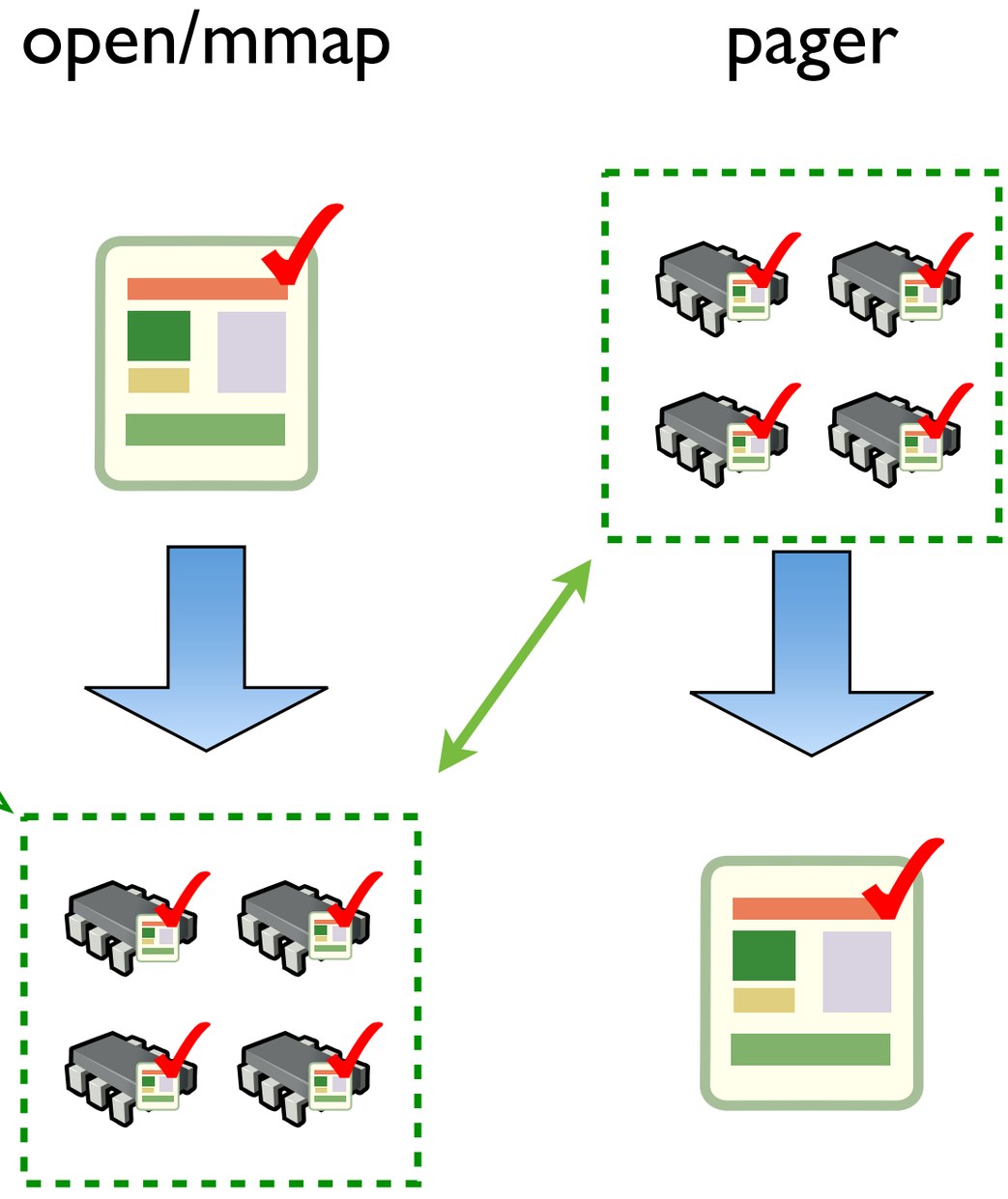


Solution: strengthen object invariants

- Object invariants: properties *always hold* for the object

It can only contain files that the pager has access to (i.e., opened by the same process)

- Can be reasoned about locally



Pager in C#

```
uint HandlePageFault(Process
p, Pointer addr, ...) {

...
var r = p.Space.Find(addr);
...
if (r.File != null) {
  var r = r.File.Read(...);
  ...
}
}
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ensures $r \neq null \rightarrow r.ObjInvariant()$
$\wedge$ *r.GhostOwner == GhostOwner;*

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Space.GhostOwner == this

File≠null→File.GhostOwner == GhostOwner ...

ensures *r≠null→r.ObjInvariant() ∧ r.GhostOwner == GhostOwner;*

r.File.GhostOwner == r.GhostOwner == space.GhostOwner == p

Security Invariant

Contract.Assert(r.File. GhostOwner == p);

AddressSpace in Dafny

```
class AddressSpace {
  var GhostOwner: Process;
  var Head: MemoryRegion;

  ...

  method Find(address:
Pointer)
  returns (ret: MemoryRegion)
  requires ObjInvariant();
  ensures ObjInvariant();

}
```

ensures *r≠null→r.ObjInvariant()*
∧ r.GhostOwner == GhostOwner;

AddressSpace in Dafny

- Heavy verification effort
- 730 lines of code
- ~200 lines of annotations

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  var GhostOwner: Process;
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  ...

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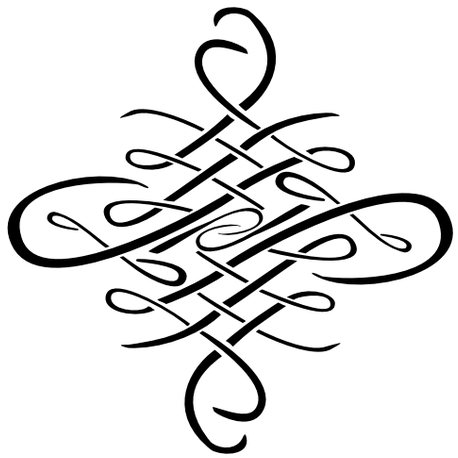
ensures $r \neq null \rightarrow r.ObjInvariant() \wedge r.GhostOwner == GhostOwner;$

Combining Dafny & CC



Dafny

ghost variables

Assume()

```
...
[Ghost] Foo GhostOwner;
Find(...) {
...
Assume(...);
...
}
```

C# + code contracts

Experience

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    - Less components (isolation & end-to-end mechanisms)

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	Line of code
Full system	13M
Linux kernel	1M
ExpressOS	15,932
Annotation	438

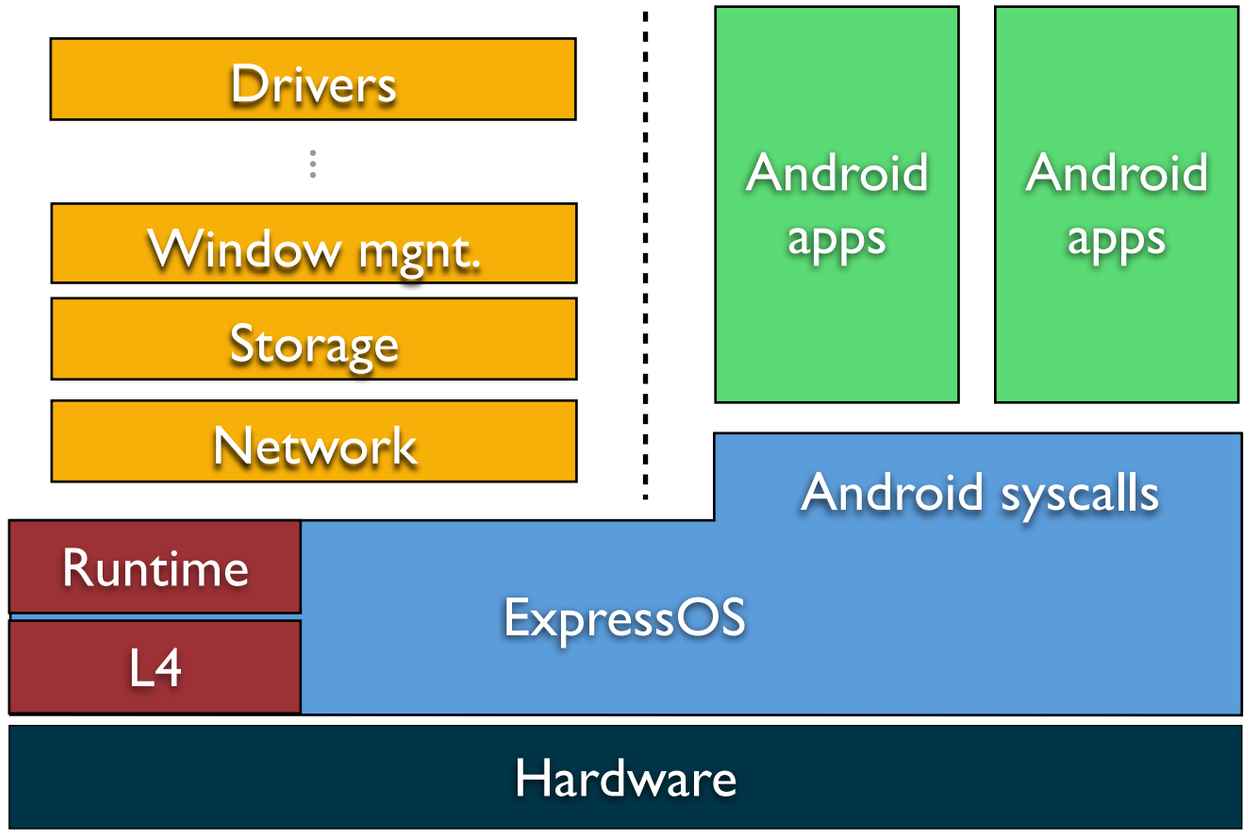
- Code contracts + Dafny: 2.8% annotation overhead

Experience on verification

- Code contracts are *mostly* sufficient
  - Plus ghost variables and the concepts of ownerships
- Dafny for the rest

Implementation

- Build on top of L4::Fiasco
- Use L4Android to implement system services
  - Turning Linux into a microkernel server
- Sufficient to run the Android web browser and this presentation

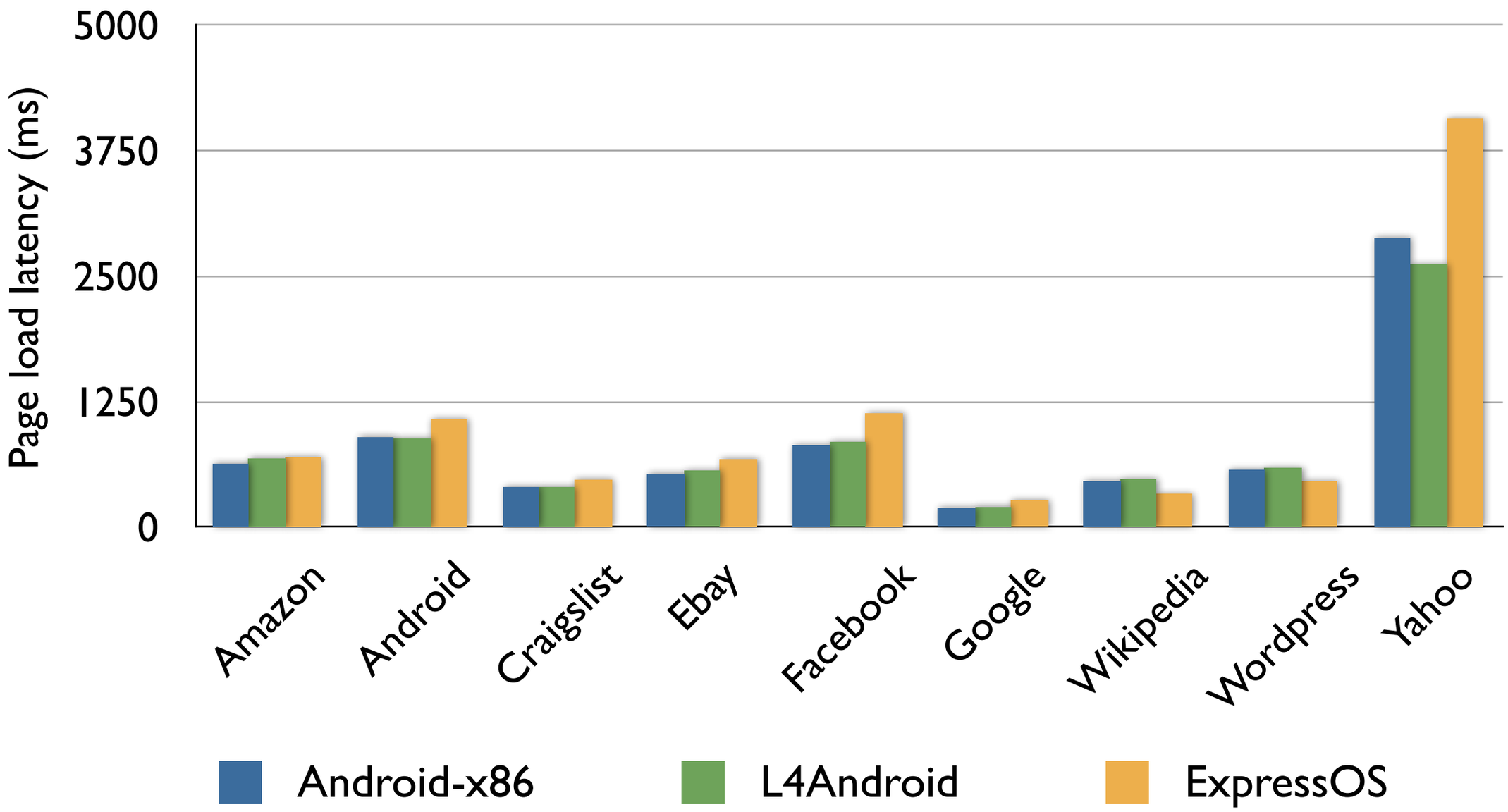


Security analysis

- Studied 742 vulnerabilities from CVE (from Jun, 2011~Jun, 2012)
- 383 of them affect Android
- ExpressOS prevents 364 (95%) of them

	Num	Prevented
Core kernel	9	9
Library of apps	102	102
Services	240	226
Applications	32	27

Page load latency on web browsing



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Conclusion

- ExpressOS: *a high assurance OS that runs Android applications*
  - Define *security invariants*
    - *Isolate* vulnerabilities of components
    - Verify security invariants *directly*
- Practical approach to establish high assurance in real-world systems

Thank you!

Source code available at:

https://github.com/ExpressOS/expressos