Secure Cooperation of Untrusted Components

Cutting Edge Research

Winter term 2022/23

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Outline

- Motivation
- Access Control
- The Object Capability Paradigm
- A Capability Type System
- Conclusion and Future Work

1 Motivation

A sorting library in Java

- You just found the "*best list sorting class ever*" in the WWW
- Interface of the class:

```
class Sorter {
  ...
  public void sort(List<? extends Comparable> list) {
    ...
  }
}
```

- Your code:

```
List<Contact> contacts = ...;
Sorter sorter = new Sorter();
sorter.sort(contacts);
```

- Your belief: `sort()` only uses `Contact.compareTo()`

1 Motivation

A sorting library in Java

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- Interface of the class:

```
class Sorter {
   ...
   public void sort(List<? extends Comparable> list) {
      ...
   }
}
```

```
Socket sock = new Socket(...);
PrintStream stream = new PrintStream(...);
Contact c = (Contact)list.get(i);
stream.println(c.getEMail());
```

- Your code:

```
List<Contact> contacts = ...;
Sorter sorter = new Sorter();
sorter.sort(contacts);
```

- Your belief: `sort()` only uses `Contact.compareTo()` **???**

Principle of least authority (POLA)

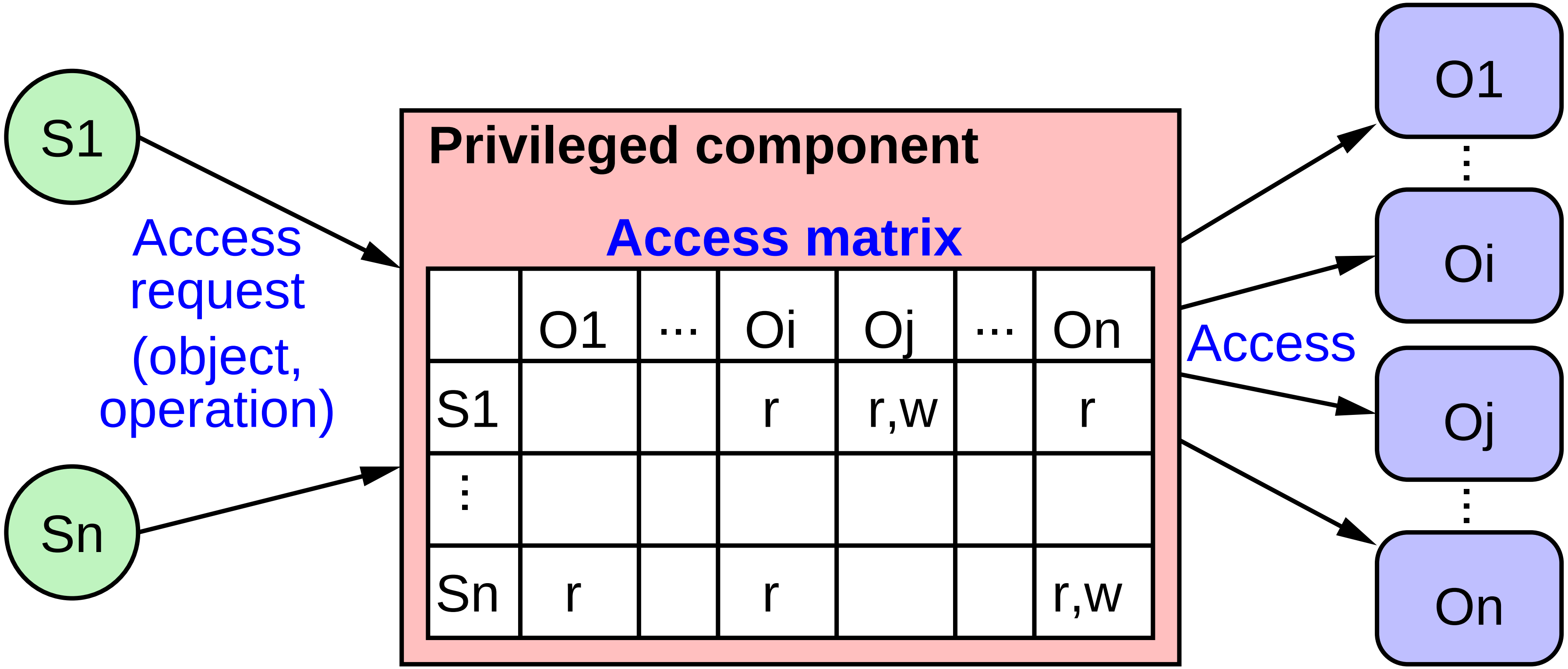
> *A software component should receive just the authority required to fulfill its intended purpose* [1]

- Difference between *authority* and *permission* [2][3]
  - *authority* also includes indirect effects
  - e.g., component may make another component perform an action, which is not directly permitted
  - e.g., action may be permitted but not available
- Basis: access control mechanisms
  - access matrix
  - access control lists (ACLs), capabilities

2 Access Control ...

Classical implementation of access control

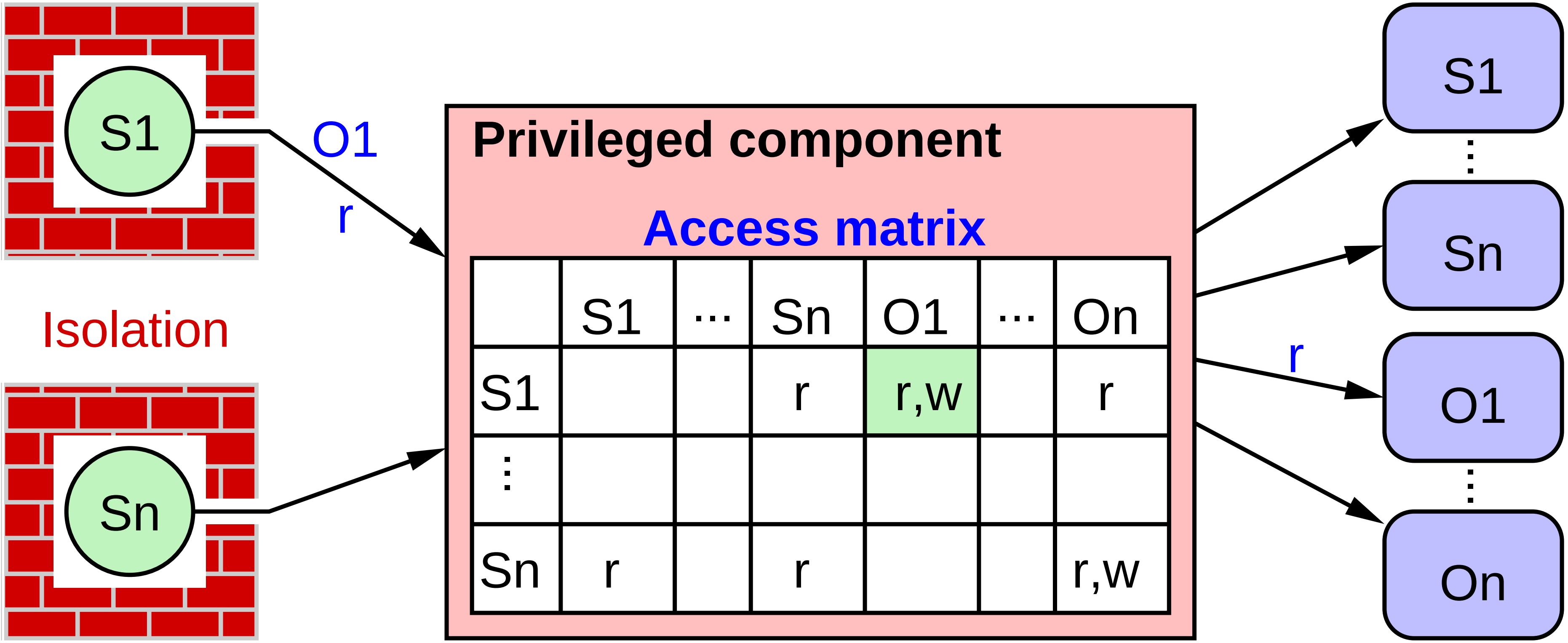
- Textbook figure:
  - subjects act upon objects
  - accesses are mediated via access matrix



	O1	...	Oi	Oj	...	On
S1			r	r,w		r
⋮						
Sn	r		r			r,w

Classical implementation of access control

- More realistic:
  - subjects are objects that may actively perform operations
  - subjects have direct access only to a privileged component



Privileged component

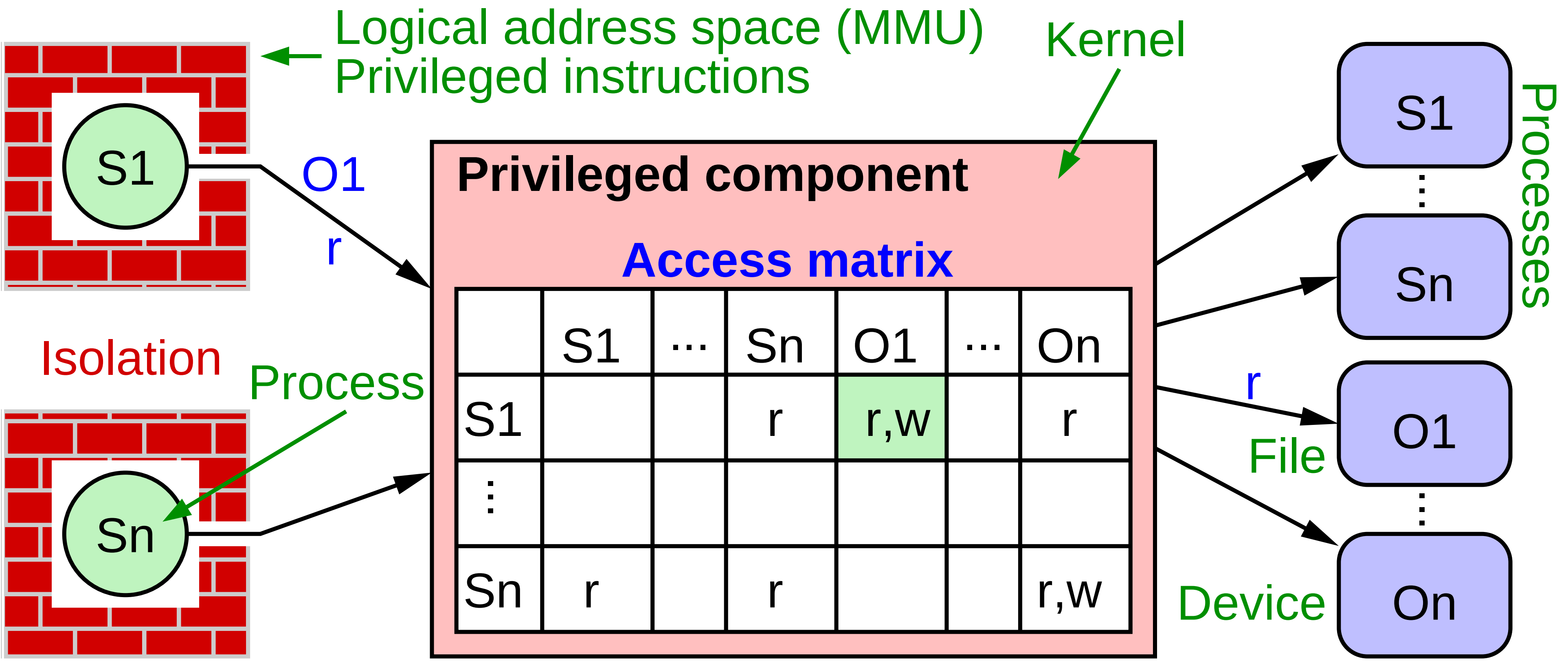
Access matrix

	S1	···	Sn	O1	···	On
S1			r	r,w		r
⋮						
Sn	r		r			r,w

2 Access Control ...

Classical implementation of access control

- Example: Linux
  - subjects = processes, isolated via hardware
  - all accesses mediated by the kernel



Access matrix

	S1	···	Sn	O1	···	On
S1			r	r,w		r
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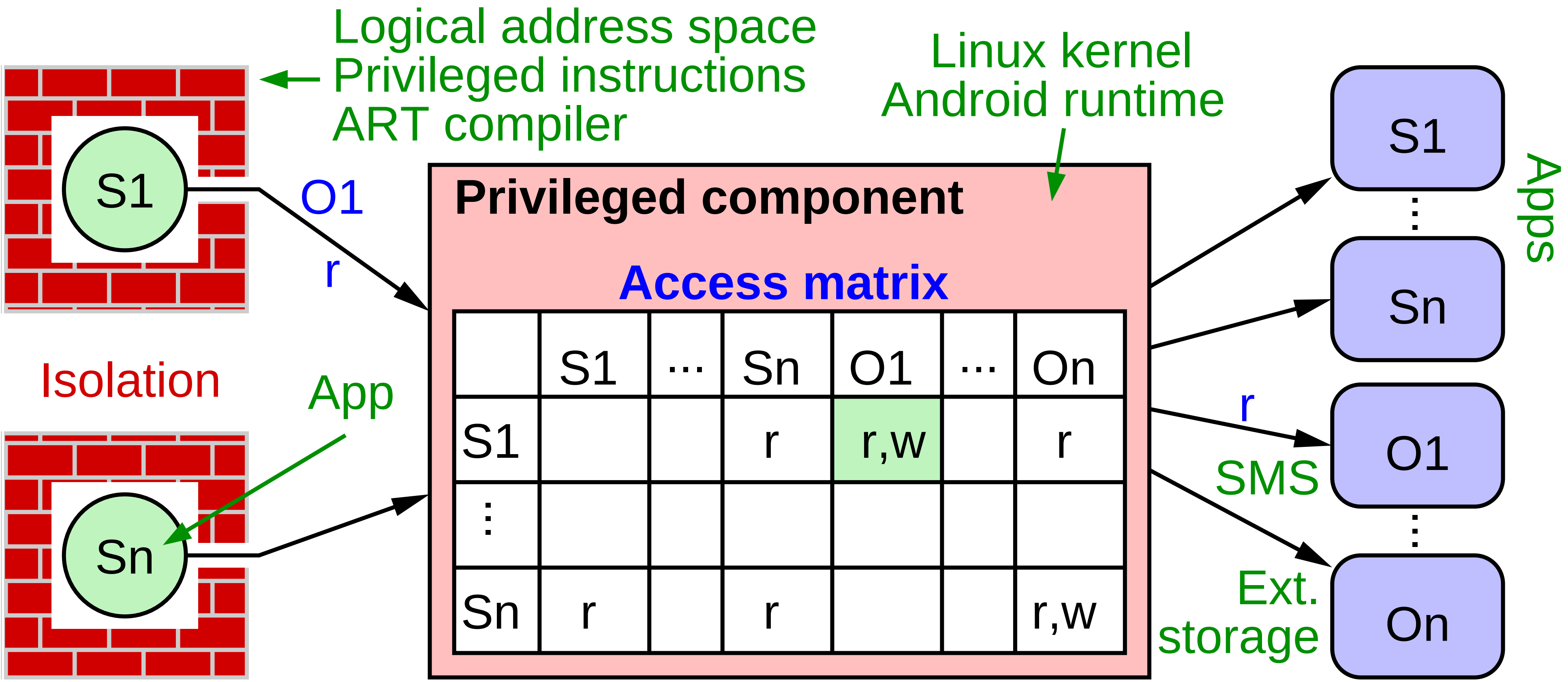
Classical implementation of access control

- Example: Android
  - subjects = apps, objects = subsystems
  - accesses mediated by kernel and runtime



	S1	···	Sn	O1	···	On
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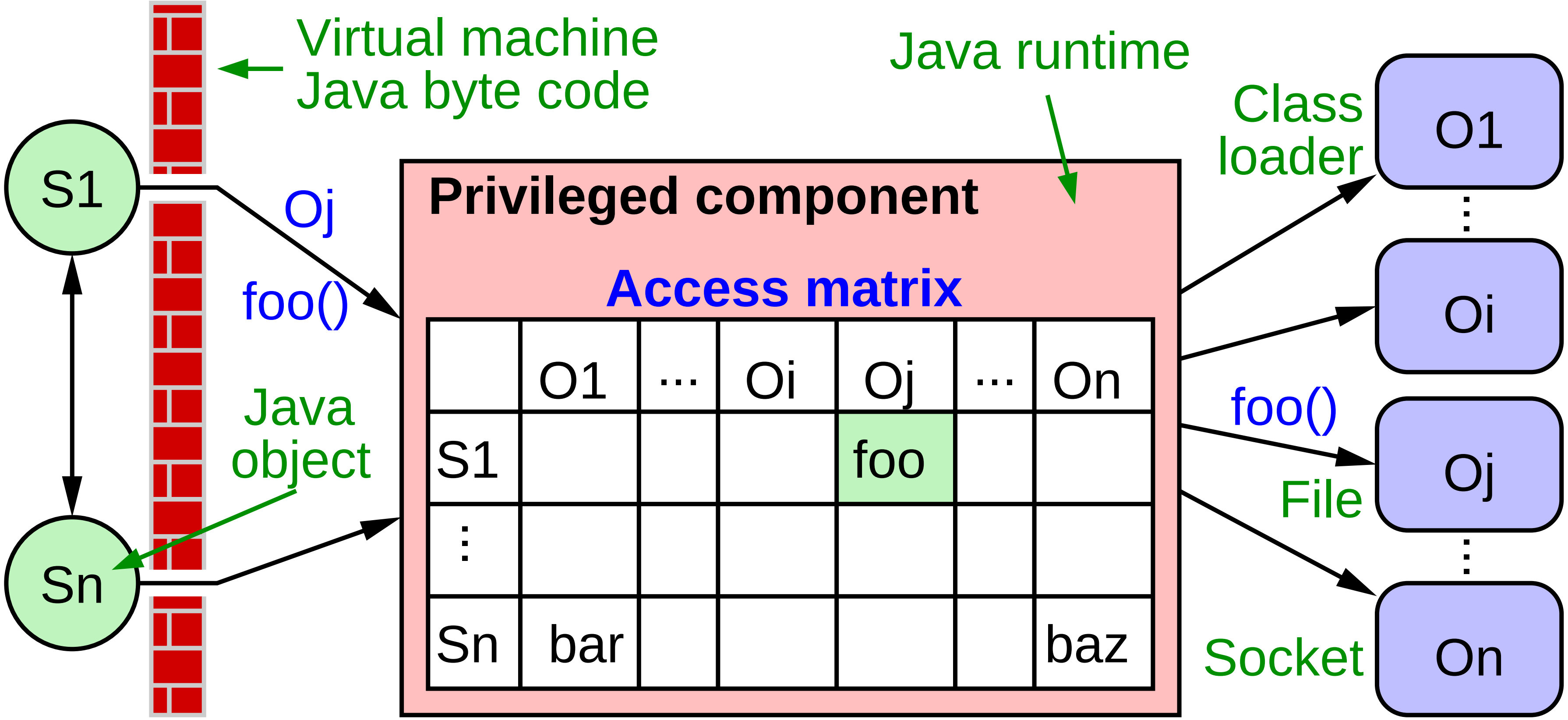
2 Access Control ...

Classical implementation of access control

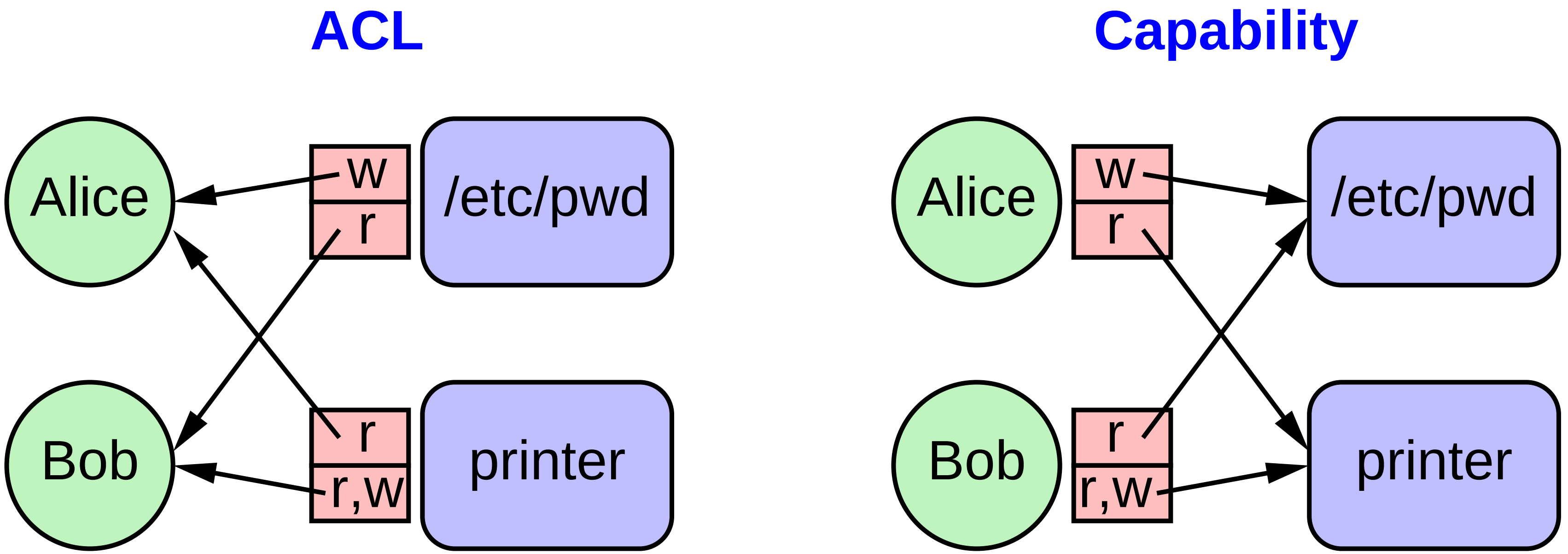
- Example: Java security manager
  - subjects = Java objects, not fully isolated
  - Java runtine mediates method calls on ‘critical‘ objects



	O1	···	Oi	Oj	···	On
S1				foo		
⋮						
Sn	bar					baz

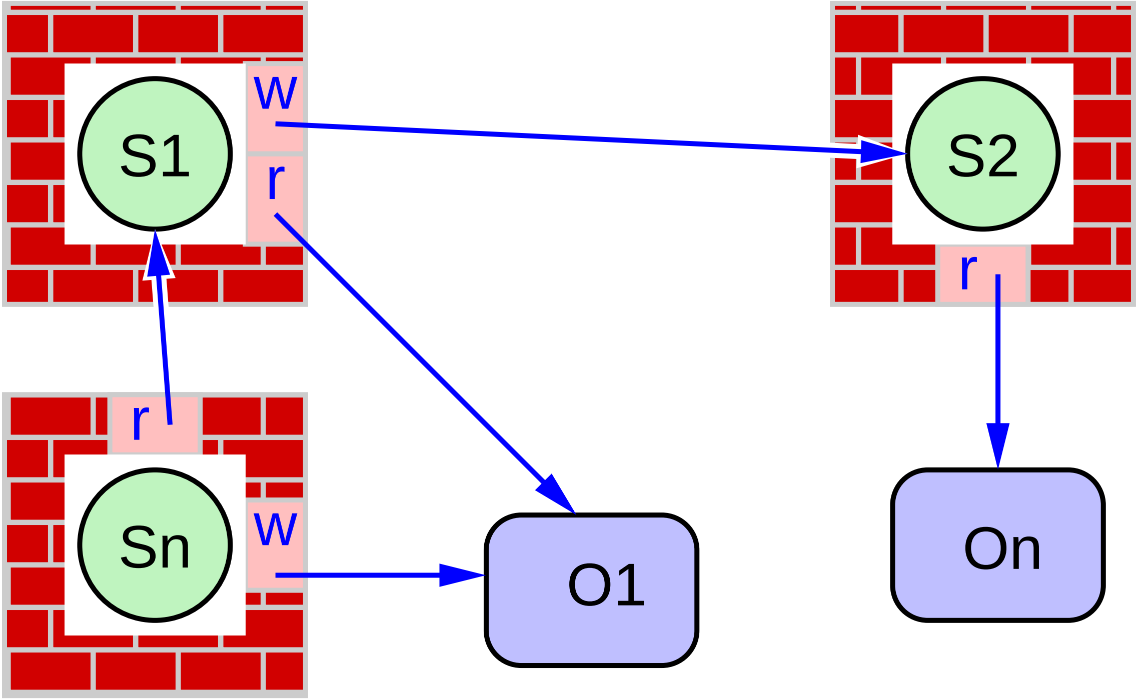
Access control using capabilities

- Capability: unforgeable information **given to** a subject, enabling it to perform operations on an object
  - inseparably combines designation with authority [4]
- Comparison:



Access control using capabilities

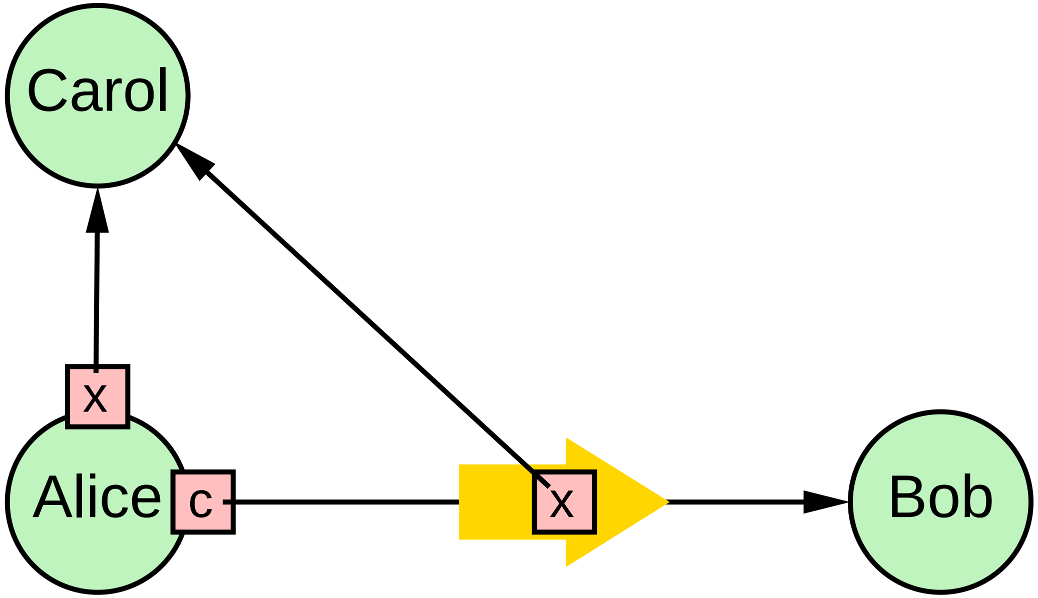
- Capability: unforgeable information **given to** a subject, enabling it to perform operations on an object
  - inseparably combines designation with authority [4]
- Results in decentralized access control



Dynamics of access permissions

- How can the acess matrix be modified at runtime?
  - changing the access matrix must require proper authority!
- ACLs
  - typically: objects have a unique *owner*
  - owner is allowed to change ACL arbitrarily
- Capabilities
  - capabilities may be passed between subjects
  - but not arbitrarily: passing a capability requires a capability! [4]
  - capabilities may be weakened (attenuated), but not amplified
  - capabilities also support revocation [4]
    - by using the caretaker pattern [5]

Dynamics of access permissions



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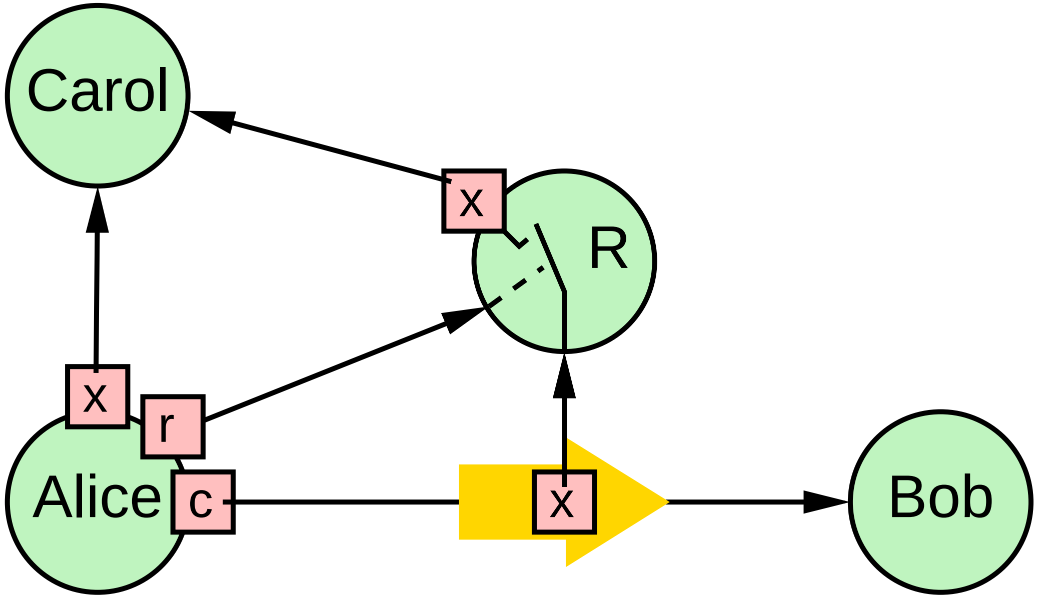

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Discussion

- Classical implementation
  - granularity of subjects is often restricted
  - permissions must be checked for each access
  - centralized mediator can be a bottleneck
  - privileged component can lead to security problems
  - restricted dynamics (e.g., no delegation)
- Capabilities
  - allow fine grained subjects
  - allow delegation of authority
  - access restrictions can be enforced by construction
    - i.e., no (or less) checks at runtime

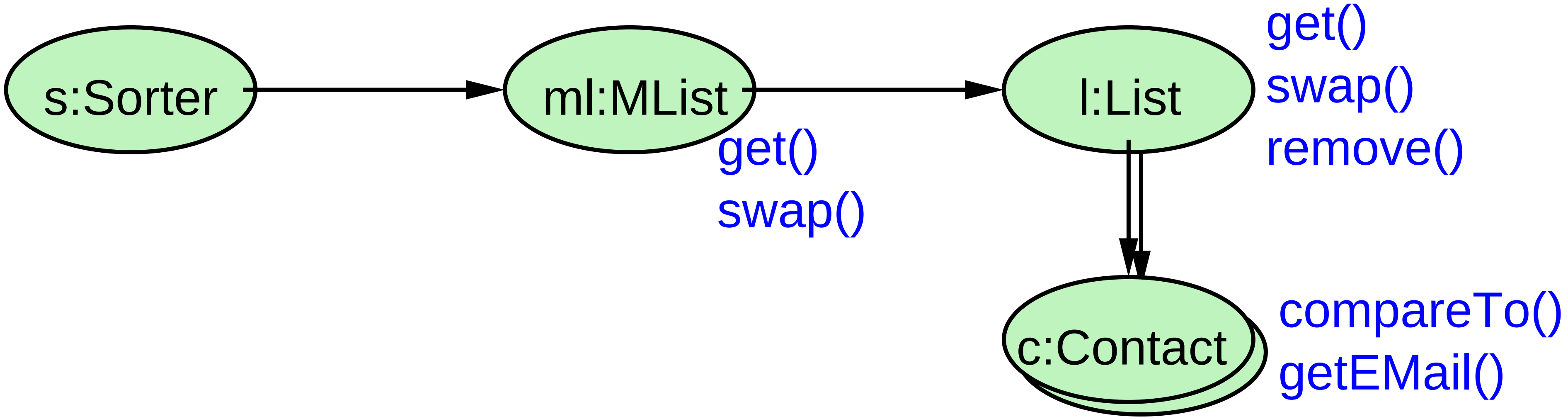
3 The Object Capability Paradigm [5][6]

- Basis: pure object oriented programming
  - everything is an object (even the subjects)
  - access to attributes only via method calls
- An object reference is a capability to access the object
  - note: no distinction is made between different operations
  - i.e. the capability allows to call all available methods
- How can an object A receive a capability to B? [6]
  - if A creates B, A has a reference (capability) to B
  - A can receive the reference to B from another object C
    - as an argument of A's constructor
    - as an argument of a method call (when C calls A)
    - as a result of a method call (when A calls C)

The Object Capability Paradigm ...

Attenuation of authority

- How can we minimize the authority granted by a reference?
- Answer: membrane pattern [3][5]
  - wrap the object into a membrane that provides less methods and/or restricted methods (that may return membranes)
  - i.e., membrane acts as fine-grained capability
- In the `Sorter` example:



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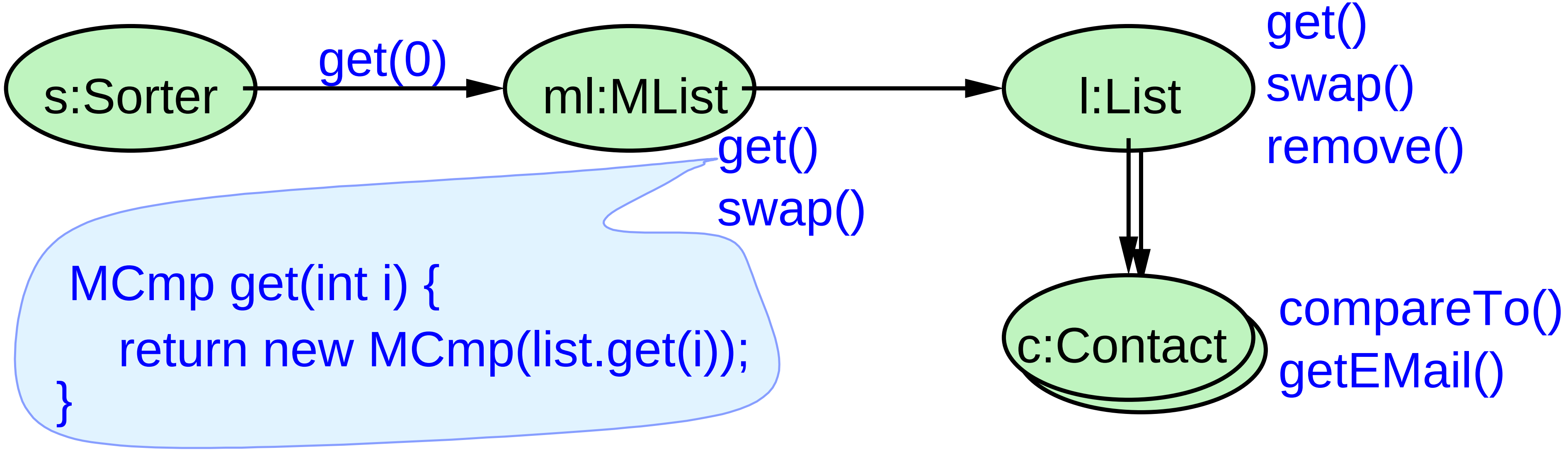

```
MCmp get(int i) {
   return new MCmp(list.get(i));
}
```

Attenuation of authority

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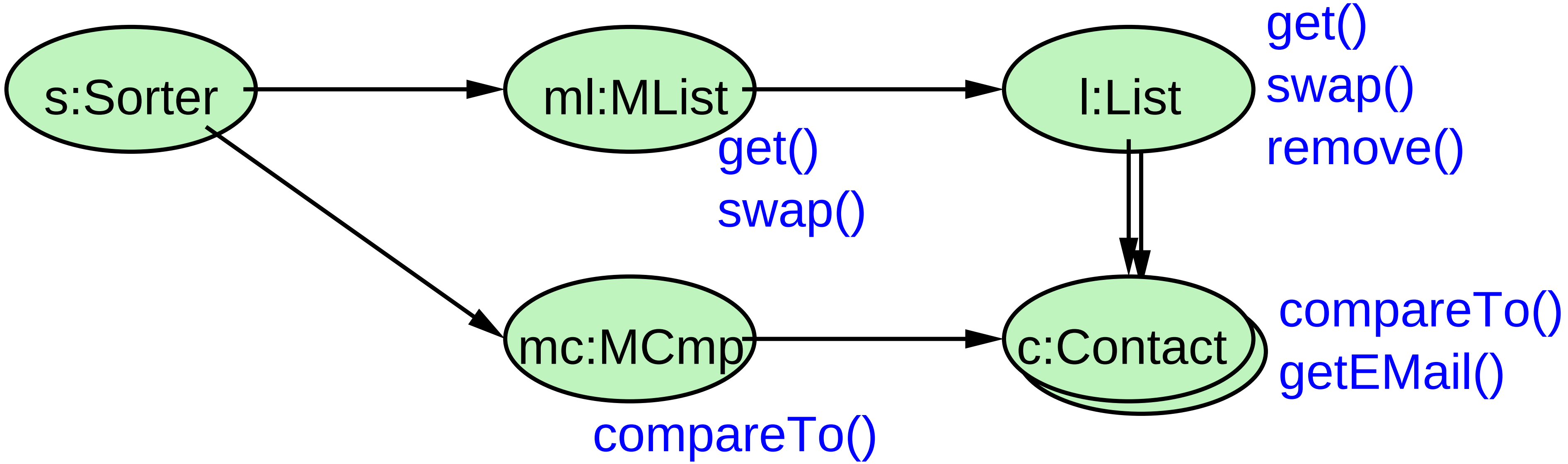


The Object Capability Paradigm ...

Secure programming languages [3][7]

- Based on the object capability paradigm and security patterns
- Foundations of security: [8]
  - memory safety: references cannot be forged
  - object encapsulation: no data access without reference
    - implies: no static methods / attributes
- Remaining shortcomings:
  - system can be attacked ‘from below’ [9]

    ⇒ must only permit code written in the secure language
    ⇒ use a secure *intermediate* language (byte code)
  - how can we know the minimal required access rights?
  - run time overhead induced by (cascaded) membranes

4 A Capability Type System

- Most programming languges are typed
- A reference type specifies requirements on the referenced object
  - e.g. `Comparable` requires that the object provides a method `compareTo()`
- A reference type also restricts the use of the referenced object
  - `Comparable` itself does not allow to invoke `getEMail()`
- Thus, types can be used to specify required / granted rights
- Idea: split capability into two parts
  - reference controls whether object can be accessed or not
  - type of reference variable controls the permitted methods
- Additional security requirements:
  - a method can be called only if both type and object permit it
  - type casts must not allow to amplify authority

4.1 Types [10]

- **Type**: a specification of properties of data objects
  - or: a collection of objects with specified properties
- **Type system**: set of rules assigning a type to language constructs, such as variables, expressions, objects, ...
- **Type checking**: verifying and enforcing the constraints of types
- For ease of presentation: we just consider interface types
- An **interface type** defines all available / usable methods, together with their argument and result types
  - for simplicity: we just consider one argument and one result
- Important relation: **subtype** relation
  - S is subtype of T, if each object of type S also has type T
  - usually written as $S <: T$, **here**: $T \leq S$

Types ...

Formal representation of types

- Type: $\mathcal{T} = \mathcal{MS}^{\mathbb{A}^*}$
  - a type defines a state for each method
    - i.e., it maps a string to the corresponding method state
  - $\mathbb{A}^*$ = the set of all strings
- Method state: $\mathcal{MS} = \mathcal{A} \times (\mathcal{M} \cup \{\perp\})$
  - a method state consists of an assertion (permission) and an optional method signature
- Assertions: $\mathcal{A} = \{\mathit{denied}, \mathit{avail}\}$
  - *denied*: type does not allow to call this method
  - *available*: type provides the method with the given signature
- Method signature: $\mathcal{M} = \mathcal{T} \times \mathcal{T}$

Types ...

Subtype relation

- S is subtype of $T \Rightarrow$ object of type S can be used where an object of type T is required
  - i.e., $o : S$ can be assigned to $v : T$ (without any further action)
- Structural typing: for $T \leq S$, S must provide a compatible method for each method provided by T
- Thus, we define:

denied < *avail*

$$\frac{T, S \in \mathcal{T} \qquad \forall a \in \mathbb{A}^* : T(a) \leq S(a)}{T \leq S}$$

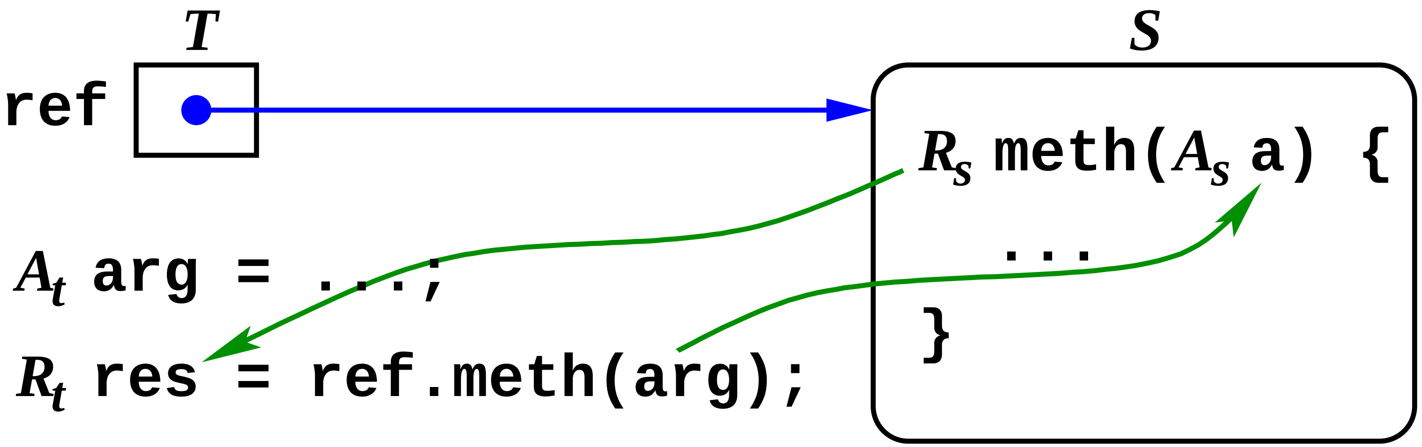
$$\frac{\begin{array}{c} t = (\pi_t, \sigma_t) \in \mathcal{MS} \\ s = (\pi_s, \sigma_s) \in \mathcal{MS} \\ \pi_t \leq \pi_s \\ \sigma_t \neq \bot \wedge \sigma_s \neq \bot \;\Rightarrow\; \sigma_t \leq \sigma_s \end{array}}{t \leq s}$$

$$\frac{\begin{array}{c} t = (A_t, R_t) \in \mathcal{M} \\ s = (A_s, R_s) \in \mathcal{M} \\ A_s \leq A_t \\ R_t \leq R_s \end{array}}{t \leq s}$$

Types ...

Covariance and contravariance

- Example:
  - `interface` T { R_t `meth(`A_t`);` }
  - `interface` S { R_s `meth(`A_s`);` } with $T \leq S$
- Situation when calling `meth`:



R_s **meth(**A_s **a) {**
...
}

A_t **arg = ...;**
R_t **res = ref.meth(arg);**

  - passing the argument requires $A_s \leq A_t$
  - passing the result requires $R_t \leq R_s$

4.2 Types as Capabilities: The COSMA Type System [11]

Security property

- If $o : T_0$ is assigned to $v : T_n$ via a sequence of casts to types $T_1, ..., T_n$, v allows to call a method m only if **all** T_i allow that
- I.e., no amplification of authority
- Property holds recursively:

```
class T0 {
   R0 m() {
      return new R0();
   }
}
class R0 {
   void m1() { ... }
   void m2() { ... }
}
```

```
interface T1 {
   R1 m();
}
interface R1 {
   void m1();
}
```

```
T0 v0 = new T0();
T1 v1 = v0;
v1.m().m1(); // OK
v1.m().m2(); // Err
T0 v2 = v1;  // Err
```

Types as Capabilities: The COSMA Type System ...

Optional methods

- Type system is still too restrictive (no downcast at all)
- We want to allow a **limited** downcast
  - i.e. only if the source type permits it
- Additional assertion: *optional* $\in \mathcal{A}$
  - *optional* means that the method may or may not be available
    - calling the method is permitted,
    - but there is no guarantee that the method is available
  - order: *denied* $<$ *optional* $<$ *avail*
- We need a new “legal cast” relation: $\prec$
  - $T \prec S \;\; \Leftrightarrow$ the *static* type check will allow a cast from S to T (although it may fail at runtime)

Types as Capabilities: The COSMA Type System ...

Legal cast relation

- We allow a (down)cast from S to T, even if some method m is
  - *available* in T and *optional* in S, or
  - *optional* in T and *denied* in S

$$\frac{\begin{array}{c} T, S \in \mathcal{T} \\ \forall m \in \mathbb{A}^* : T(m) \prec S(m) \end{array}}{T \prec S}$$

$$\frac{\begin{array}{c} t = (\pi_t, \sigma_t) \in \mathcal{MS} \\ s = (\pi_s, \sigma_s) \in \mathcal{MS} \\ \neg(\pi_t = \mathit{avail} \wedge \pi_s = \mathit{denied}) \\ \sigma_t \neq \bot \wedge \sigma_s \neq \bot \;\Rightarrow\; \sigma_t \prec \sigma_s \end{array}}{t \prec s}$$

$$\frac{\begin{array}{c} t = (A_t, R_t) \in \mathcal{M} \\ s = (A_s, R_s) \in \mathcal{M} \\ A_s \prec A_t \\ R_t \prec R_s \end{array}}{t \prec s}$$

Types as Capabilities: The COSMA Type System ...

Runtime actions

- If we have $T \prec S$, but $T \not\leq S$, we need to perform some actions at runtime
- $\exists m : m$ is *available* in T and *optional* in S:
  - we need a type check to ensure that m is actually available
- $\exists m : m$ is *optional* in T and *denied* in S:
  - we need a membrane to ensure that m cannot be called via T
  - let M be the type of this membrane
  - requirement: $T \leq M$, M doesn't grant more authority than S
  - problem: all $x \in \mathcal{A}$ with *optional* $\leq x$ permit calling m
  - solution: new element *unavailable* with *optional* $<$ *unavail*
    - asserts that the object does **not** provide the method

Types as Capabilities: The COSMA Type System ...

Creating membranes

- We first extend the $\prec$ relation properly:

$$\frac{\begin{array}{c} t = (\pi_t, \sigma_t) \in \mathcal{MS} \\ s = (\pi_s, \sigma_s) \in \mathcal{MS} \\ \neg(\pi_t = \mathit{avail} \wedge (\pi_s = \mathit{denied} \vee \pi_s = \mathit{unavail})) \\ \sigma_t \neq \bot \wedge \sigma_s \neq \bot \;\Rightarrow\; \sigma_t \prec \sigma_s \end{array}}{t \prec s}$$

- Next, we need a rule to determine the membrane type
  - let $T \cap_r S$ be the smallest subtype of T that does not grant more rights than S
  - for contravariance: $T \cap^r S$ is the largest supertype of S that does not grant more rights than T

Types as Capabilities: The COSMA Type System ...

Restricting method permissions

- Partial order: *denied* $<$ *optional* $<$ *avail*
  unavail

- $t \cap_r s$:

$t \setminus s$	*denied*	*optional*	*avail*	*unavail*
denied	*denied*	*denied*	*denied*	*denied*
optional	*unavail*	*optional*	*optional*	*unavail*
avail	- - -	*avail*	*avail*	- - -
unavail	*unavail*	*unavail*	*unavail*	*unavail*

- $t \cap^r s$:

$t \setminus s$	*denied*	*optional*	*avail*	*unavail*
denied	*denied*	*denied*	*denied*	*unavail*
optional	*denied*	*optional*	*avail*	*unavail*
avail	*denied*	*optional*	*avail*	*unavail*
unavail	*denied*	*denied*	*denied*	*unavail*

Types as Capabilities: The COSMA Type System ...

Restricted subtype

$$\frac{T, S \in \mathcal{T}}{T \cap_r S = \lambda m.(T(m) \cap_r S(m))}$$

$$\frac{\begin{array}{c} t = (\pi_t, \sigma_t) \in \mathcal{MS} \\ s = (\pi_s, \sigma_s) \in \mathcal{MS} \end{array}}{t \cap_r s = (\pi_t \cap_r \pi_s, \sigma_t \cap_r \sigma_s)}$$

$$\frac{s \in \mathcal{M} \cup \{\perp\}}{\perp \cap_r s = \perp} \qquad \frac{t \in \mathcal{M} \cup \{\perp\}}{t \cap_r \perp = \perp}$$

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Types as Capabilities: The COSMA Type System ...

Restricted supertype

$$\frac{T, S \in \mathcal{T}}{T \cap^r S = \lambda m.(T(m) \cap^r S(m))}$$

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$$\frac{s \in \mathcal{M} \cup \{\perp\}}{\perp \cap^r s = \perp} \qquad \frac{t \in \mathcal{M} \cup \{\perp\}}{t \cap^r \perp = \perp}$$

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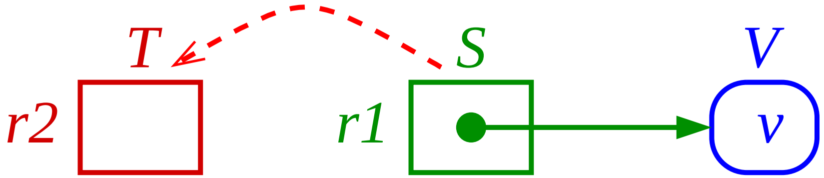
Types as Capabilities: The COSMA Type System ...

Runtime cast actions

- Situation:



Types as Capabilities: The COSMA Type System ...

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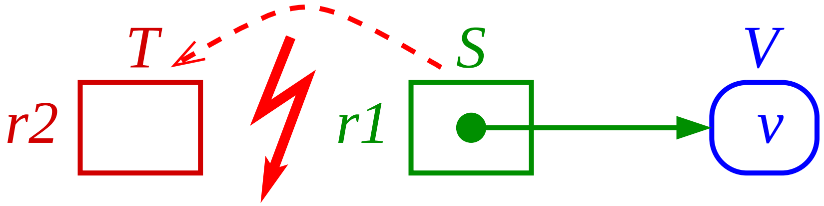

- $T \not\preceq S$: static type error!
    - is already determined when loading a component

Types as Capabilities: The COSMA Type System ...

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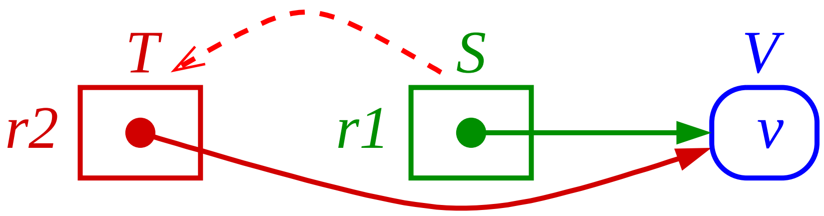

- $T \not\leq S$: static type error!
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- $T \leq S$: assign reference as is
  - access restrictions of S are also enforced by T

Types as Capabilities: The COSMA Type System ...

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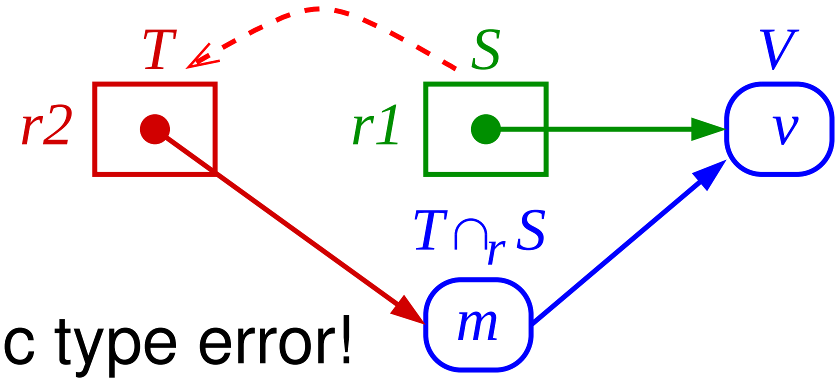
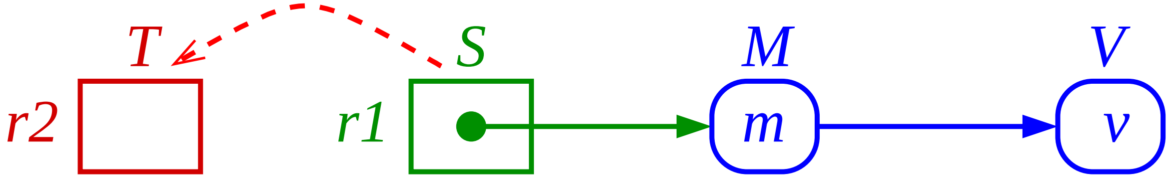


- $T \not\leq S$: static type error!
  - is already determined when loading a component
- $T \leq S$: assign reference as is
  - access restrictions of S are also enforced by T
- Otherwise: create a membrane with type $T \cap_r S$
  - access restrictions of S are enforced by membrane and T

Types as Capabilities: The COSMA Type System ...

Cascading membranes

- What happens if the assigned object already is a membrane?
- Situation:



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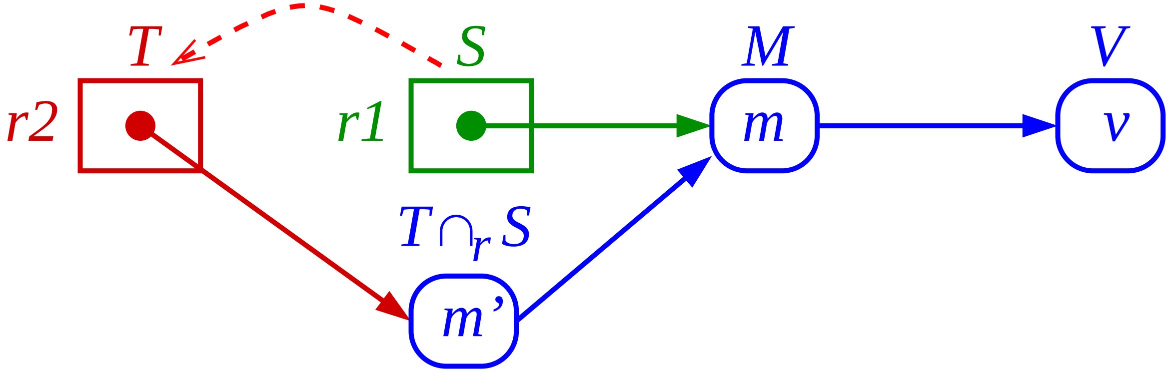

- Cascading membranes can lead to severe inefficiency
  - method calls are forwarded multiple times

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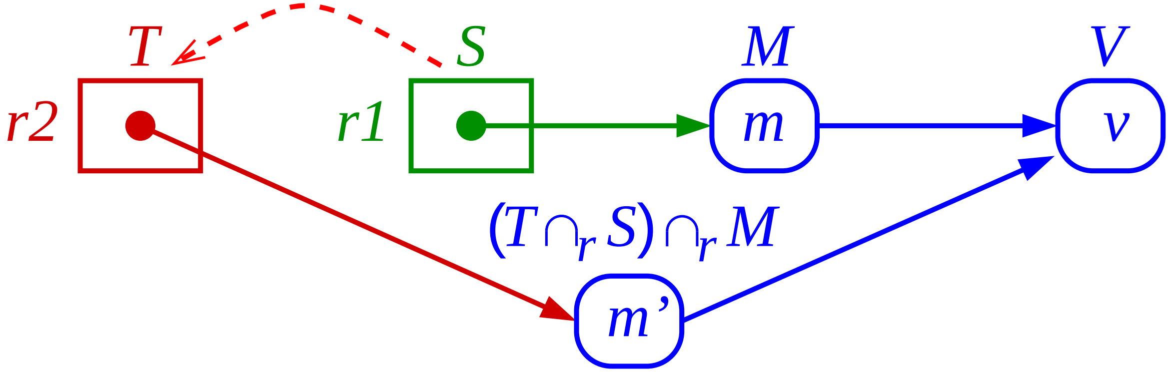

- Cascading membranes can lead to severe inefficiency
  - method calls are forwarded multiple times
- Solution: new membrane includes restrictions of M
  - can forward calls directly to the real object

4.3 Extensions

- Remove security restrictions inside a single component
  - introduce security contexts and a generic permission "*local*"
  - a reference that assures that the object is in the local context can be downcasted without limitation
- Add classes to the type system
  - direct access to attributes is allowed via a *local* reference
- Add array types
  - array modeled as class with `read()` and `write()` method
- Allow unsafe casts, i.e. unsafe covariant types
  - i.e. if S is subtype of T, allow S[] being used as T[]
  - problem: T[] has `write(`T `e)`, while S[] has `write(`S `e)`
    - S[] is not a subtype of T[], since S is not a supertype of T
  - may result in a runtime type error when `write()` is called

4.3 Extensions ...

- Additional generic permissions, e.g. "*transferable*"
  - (only) a *transferable* reference can be passed to a different context
  - allows implementation of *confined* types [12]
  - e.g., objects of a class declared as *non-transferrable* can never be accessed from another context
- Unifying structural and nominal typing [13][14]
  - advantage of structural typing: no need to explicitly declare subtype relationship ("*implements*")
  - problem of structural typing: cannot express semantic restrictions
  - solution: type system allows to specify a semantic category for each method

5 Conclusion and Future Work

- Software systems should obey the POLA
- Capabilities combine designation with authority
- Object capability systems use references as capabilities
  - fine grained access control requires the use of membranes
- Types can serve as a specification of fine grained access rights
  - type system must not allow amplification of rights
  - (restricted) downcast is possible by introducing membranes
  - often, access rights need not be checked at runtime

- Future work:
  - extension of type system (e.g., revocation)
  - full implementation of a virtual machine using the type system
    - including modular operating system

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