Verified secure kernels and hypervisors for the Cloud

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CEA LIST

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Plan

The need for isolation

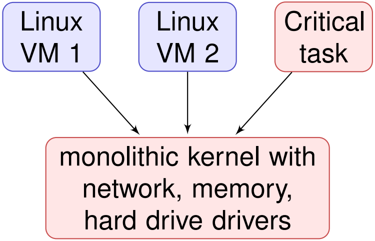
- The cloud mutualizes ressources (CPU time, memory, network bandwidth...) between tasks of several clients

➜ Often, each single computer in the cloud is shared

➜ Isolation between the tasks
  - Prevent a task from altering the behavior of another task (isolation)
  - Dually, prevent information from being accessed, modified, or made unavailable (information security/integrity and confidentiality)
- Anaxagoros:
  - Aims to provide the same level of isolation as physical separation
  - Allows secure, but dynamic and efficient ressource sharing
  - Favors reusability/ease of use through virtualization

Anaxagoros: Design principles

- Intensive TCB minimization



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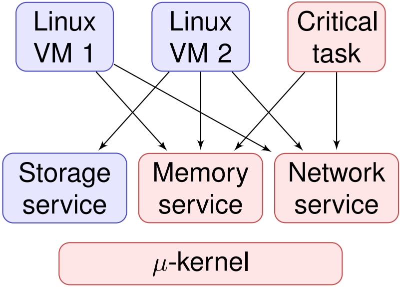
  - Moving code and data from kernel to *isolated* services
    - Microkernel approach
    - Reduce impact of a fault to users of a service



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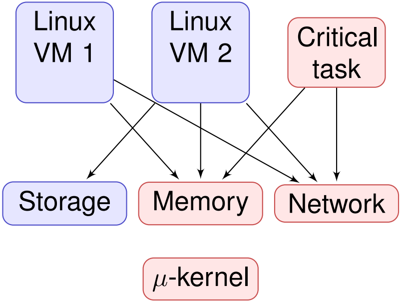

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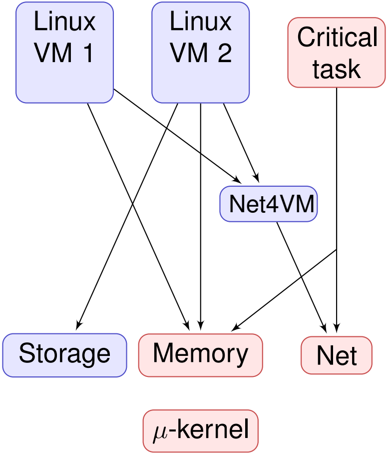
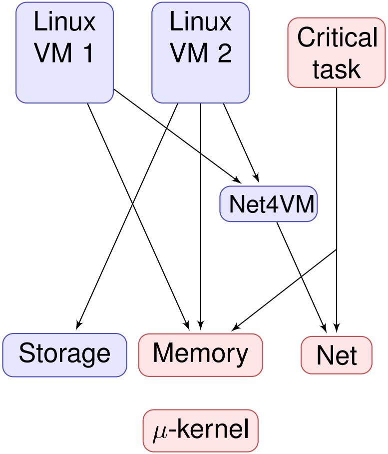
    - Exokernel/hypervisor approach
    - Reduce impact of a fault to one task
  - Hierarchical ressource allocation and services
    - Move code from root to leafs
    - Reduce impact of a fault to users of the leaf service
  - Minimal impact of a fault or attack
  - Most trusted parts (kernel and root services) are smaller and isolated
  - ➜ Amenable to formal verification



Anaxagoros: Design principles

- Fast and precise access control
  - Unique, simple mechanism for access control: capabilities (keys)
  - Formalizes the access control links:
    - ➜ Analysis of the impact of the failure of a service (= tasks that use it)
    - ➜ Analysis of the vulnerabilities of a task (= used services + μ-kernel)
    - ➜ Simplified proof of isolation (reduced to shared services)
  - Behavioral isolation of a system is reduced to isolation of a small number of services
  - Innovative implementation:
    - all operations take $O(1)$ CPU time
    - capabilities take $O(1)$ kernel and service memory



Resource security: motivation

- Original motivations
  - Anaxagoros originally built for mixed-criticality hard real-time systems
  - Non-critical tasks must not slow down critical tasks
  - ➜ Protection against denial of services insufficient
  - Must protect against slow down of services
- Causes of task slow down
  - Hardware causes: cache evictions, bus contentions
  - Software causes: preventing execution of the highest priority task
    - Unpredictable blocking on semaphores, priority inversion
    - Priority inheritance
    - Exhausted resource (e.g. memory)
  - Usual solution: over-provisionning using pessimistic assumptions
    - E.g. static scheduling and allocations
    - Schedulability analysis with priority inheritance
- An alternative solution: “predictable” scheduling
  - Scheduler is always able to execute the task it wants to elect
  - \+ Better scheduling algorithms
  - \+ Less pessimistic schedulability analysis

Resource security: implementation

New resource security principle:

Independence of allocation policies

Allocation is defined in a single, separated module

- Applications
  - Allows to state and formally prove properties on resource allocation
    - Allows sharing resources (network, CPU time, memory) with *exact* accounting ($\rightarrow$ Cloud: billing)
    - (Provably) guaranteed QoS/performance isolation; critical real-time tasks
  - Security: allows suppression of resource-related covert channel
  - Allocation becomes a separate concern $\rightarrow$ modular design, custom allocation policies
- Requires to eliminate usual “ad-hoc” design decisions, e.g.:
  - Kernel that bypass the resource allocation module
  - Using blocking locks and semaphores in the OS
  - Denial of resources (hard, especially with isolated shared services)

Resources when using a service

- Security put service and clients into separated protection domains
  - ➜ Client sends requests to services
  - Handling requests consume resources
  - ➜ Service consumes resources on behalf of the client

1. Denial of resource problem

Denial of resource

Sending requests that exhaust the resources of a service

- Ex: sending requests to an X server
  - Spend CPU time to execute the request
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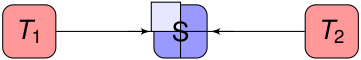

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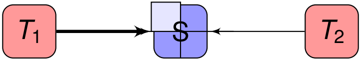

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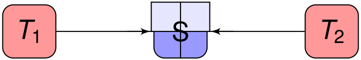

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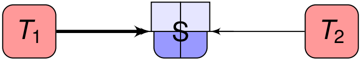

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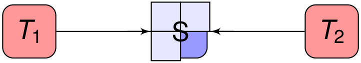

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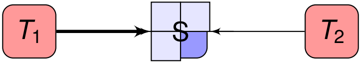

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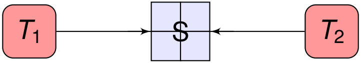

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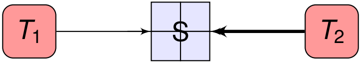

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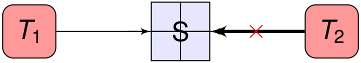

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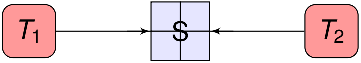

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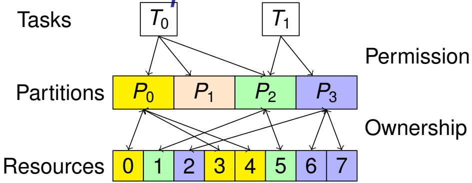
2. Resource accounting problem
   - How to attribute these resources to the client?

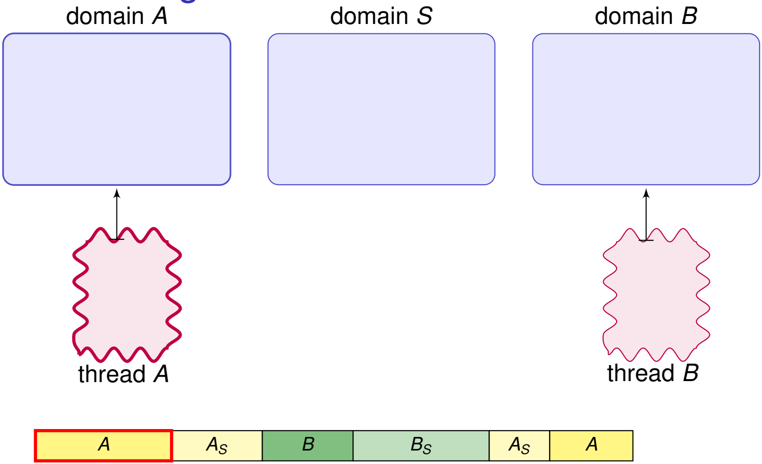
→ Our solution: complete *resource lending*

Separation between *permission* and *ownership*



- How to account for resources used by a task?
  - In a dynamic system (reallocation, resource reuse)
  - With resource sharing
- ➜ Intermediary notion of *partition* (defines ownership)
  - Each resource belongs to one, and only one, partition
  - Allocation = change of partitionning
  - No illusion of “resource creation”
  - Partition = unit to which resources are imputed/attributed
- Tasks can use *several* partitions (permission)
  - capability = right to use resources in a partition
  - e.g. right to write data, right to read&execute the code of shared libraries
  - right to change the sub-partitionning (for the allocation service)
- Definition: lending = transfer of permission, not of ownership
  - Dynamic use of resources
  - No intervention of the allocation module

Thread lending: CPU time



- Thread = unit of CPU time dispatch

→ CPU time lending by thread lending

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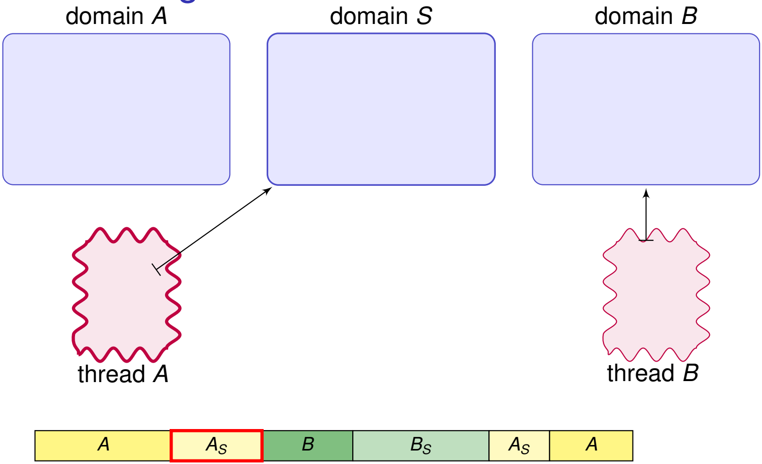

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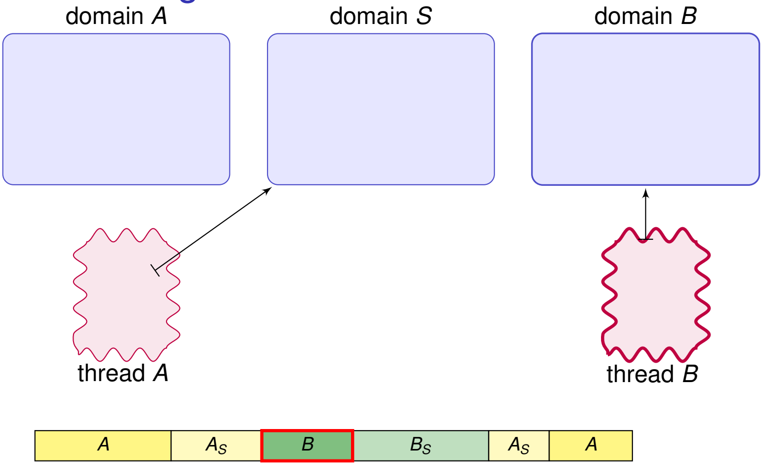

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- Execution can stop and resume in the service
  - ➜ Multithreaded service

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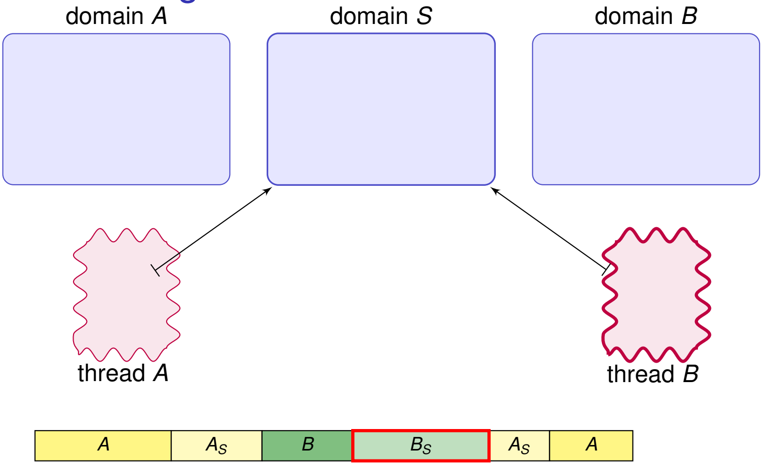

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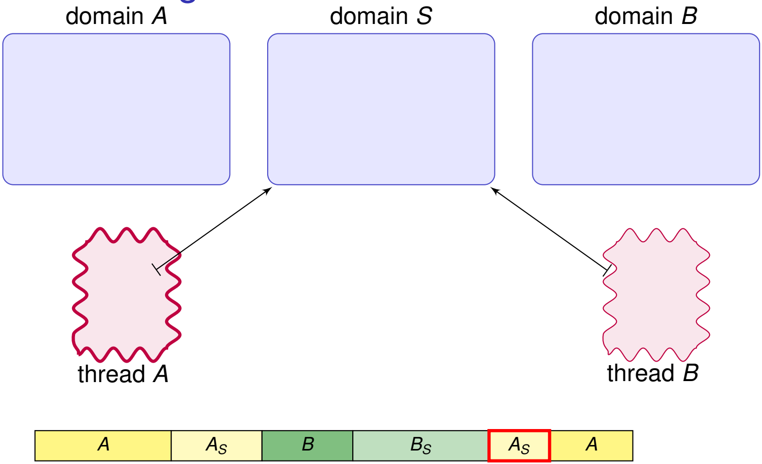

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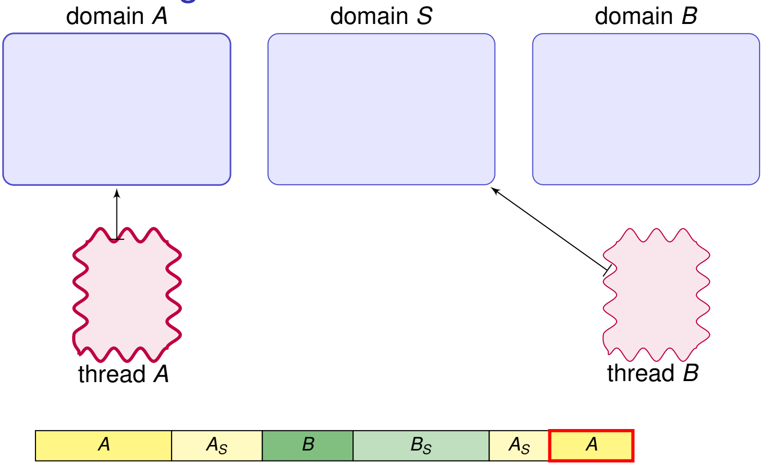

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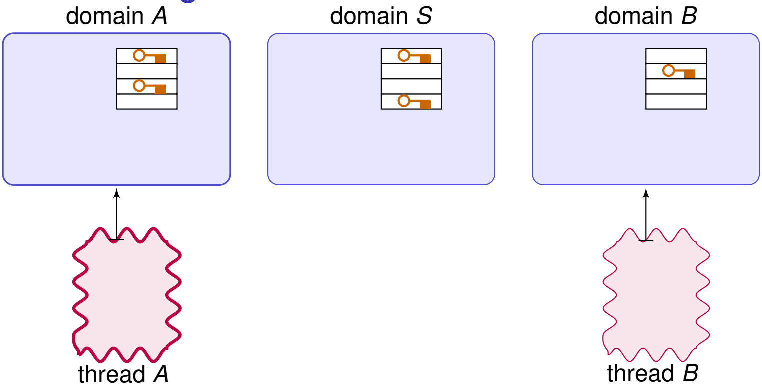
Thread lending: other resources



- Other resources must be lent (e.g. stack)
- Use a resource ⇒ own its key
- Usual approach: copy key to the service

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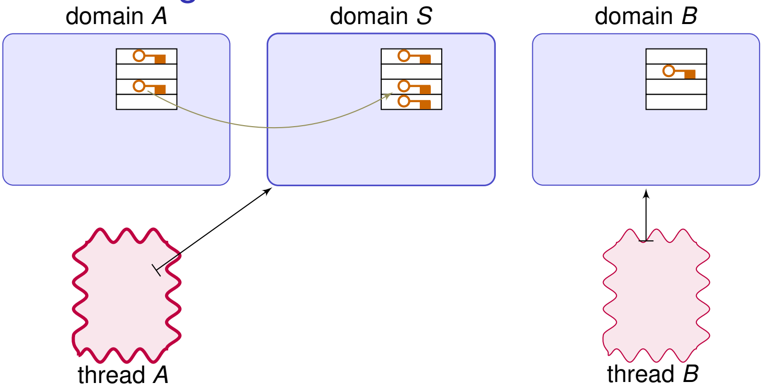

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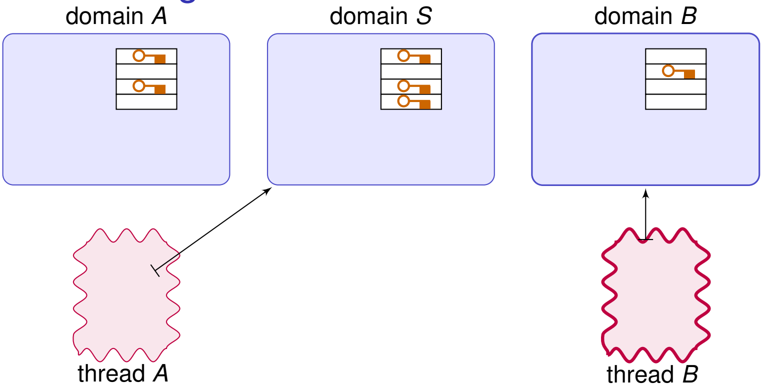

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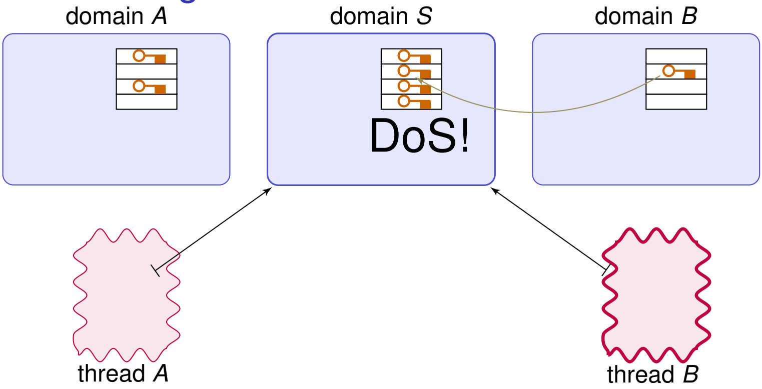
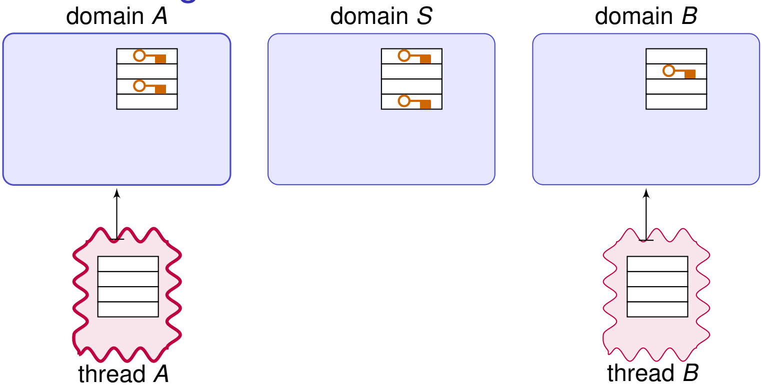


- Other resources must be lent (e.g. stack)
- Use a resource $\Rightarrow$ own its key
- Usual approach: copy key to the service
  - ➜ Storage by the service
  - ➜ DoS on the service memory
- Lending resource (to avoid DoS) can cause DoS!

Thread lending: other resources



- Solution: also lend storage for keys (and other metadata)
  - ➜ Lent keys can be stored in per-thread storage
  - + Simple model (passive object call in OO)
  - Similar mechanism for memory mappings

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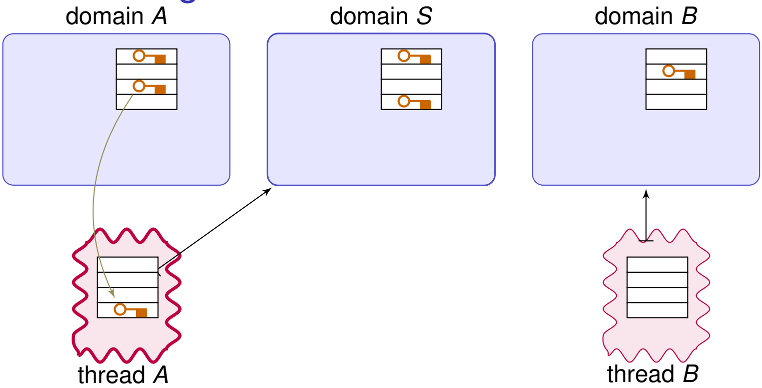

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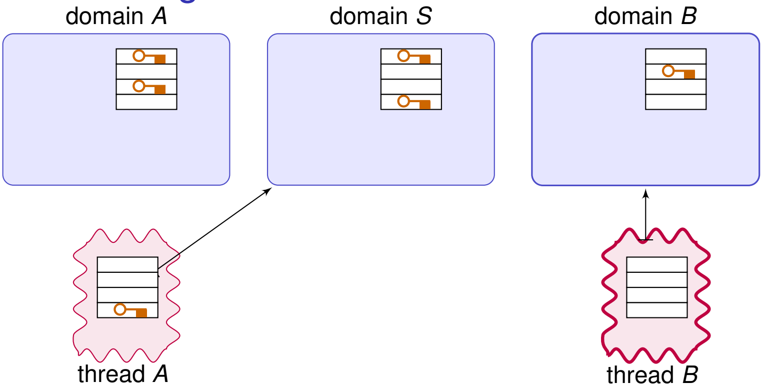

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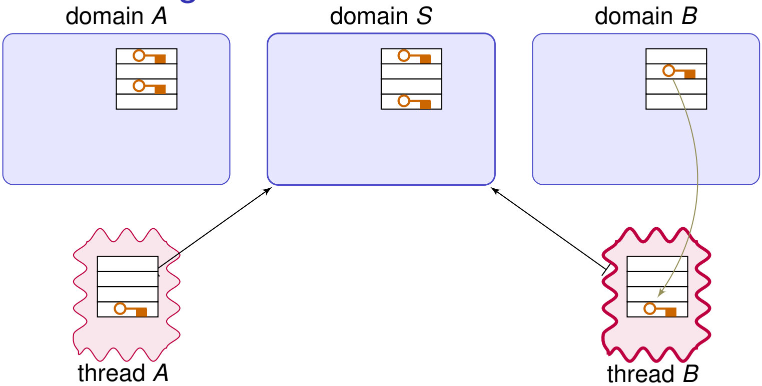

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  - + Simple model (passive object call in OO)
  - Similar mechanism for memory mappings
- Suppression de toute allocation pour la communication
  - , implemcapacitesno master object table
  - + No allocation by the service invulnerability to DoS

Plan

Proof of Programs

- Annotate source code by contracts, or spec's, with
  - Preconditions: what is supposed before the function call (`requires`)
  - Postconditions: what should be verified after the function call (`ensures`)
- Run automatic tool (like Frama-C / Jessie) which
  - Translates contracts into theorems, called proof obligations,
  - Proves them using automatic provers (like Alt-Ergo)
- Analyze proof failures (if any), complete specification
  - Loop invariants, assertions, etc.

Frama-C and ACSL language

- Frama-C : framework for analysis of C programs
  - Developed by CEA LIST and INRIA
  - Extensible plugin-oriented architecture
  - Open-source platform: http://frama-c.com
  - Includes various static and dynamic analyzers for C
    - Value analysis, test generation (PathCrawler), dependency, slicing...
- ACSL: ANSI/ISO C Specification Language
  - Common specification language for Frama-C analyzers
- Jessie plugin
  - Proof of programs (theorem proving)

Example : search in sorted array

```
//searches x in sorted array a of size l
int searchInArray(int* a, int l, int x){
  int k;

  for(k = 0; k < l; k++){
    if(a[k] == x)
      return k ;  // found, returns index
    else if(x < a[k])
      return -1 ; // not found (a sorted)
  }
  return -1 ;     // not found
}
```

```
/*@ requires l >= 0;
    requires \valid(a + (0..(l-1)));
    requires \forall integer i, j; (0 <= i <= j < l ==> a[i] <= a[j]);

    assigns \nothing;

    behavior present:
      assumes \exists integer i; (0 <= i < l && a[i] == x);
      ensures 0 <= \result < l;
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    behavior absent:
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  for(k = 0; k < l; k++){
    if(a[k] == x)
      return k ;  // found, returns index
    else if(x < a[k])
      return -1 ; // not found (a sorted)
  }
  return -1 ;     // not found
}
```

```
/*@ requires l >= 0;
    requires \valid(a + (0..(l-1)));
    requires \forall integer i, j; (0 <= i <= j < l ==> a[i] <= a[j]);

    assigns \nothing;

    behavior present:
      assumes \exists integer i; (0 <= i < l && a[i] == x);
      ensures 0 <= \result < l;
      ensures a[\result] == x;

    behavior absent:
      assumes \forall integer i; (0 <= i < l ==> a[i] != x);
      ensures \result == -1;
*/
int searchInArray(int* a, int l, int x){
  int k;
  for(k = 0; k < l; k++){
    if(a[k] == x)
      return k ;  // found, returns index
    else if(x < a[k])
      return -1 ; // not found (a sorted)
  }
  return -1 ;      // not found
}
```

which (non local) variables can be modified?

```
/*@ requires l >= 0;
    requires \valid(a + (0..(l-1)));
    requires \forall integer i, j; (0 <= i <= j < l ==> a[i] <= a[j]);

    assigns \nothing;

    behavior present:
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/*@ requires l >= 0;
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int searchInArray(int* a, int l, int x){
  int k;
  for(k = 0; k < l; k++){
    if(a[k] == x)
      return k ;  // found, returns index
    else if(x < a[k])
      return -1 ; // not found (a sorted)
  }
  return -1 ;     // not found
}
```

First behavior:
If x present in a

then returned value
is index of x in a

```c
/*@ requires l >= 0;
    requires \valid(a + (0..(l-1)));
    requires \forall integer i, j; (0 <= i <= j < l ==> a[i] <= a[j]);

    assigns \nothing;

    behavior present:
      assumes \exists integer i; (0 <= i < l && a[i] == x);
      ensures 0 <= \result < l;
      ensures a[\result] == x;

    behavior absent:
      assumes \forall integer i; (0 <= i < l ==> a[i] != x);
      ensures \result == -1;
*/
int searchInArray(int* a, int l, int x){
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  for(k = 0; k < l; k++){
    if(a[k] == x)
      return k ;  // found, returns index
    else if(x < a[k])
      return -1 ; // not found (a sorted)
  }
  return -1 ;      // not found
}
```

```
/*@ requires l >= 0;
    requires \valid(a + (0..(l-1)));
    requires \forall integer i, j; (0 <= i <= j < l ==> a[i] <= a[j]);

    assigns \nothing;

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      assumes \forall integer i; (0 <= i < l ==> a[i] != x);
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int searchInArray(int* a, int l, int x){
  int k;
  for(k = 0; k < l; k++){
    if(a[k] == x)
      return k ;  // found, returns index
    else if(x < a[k])
      return -1 ; // not found (a sorted)
  }
  return -1 ;     // not found
}
```
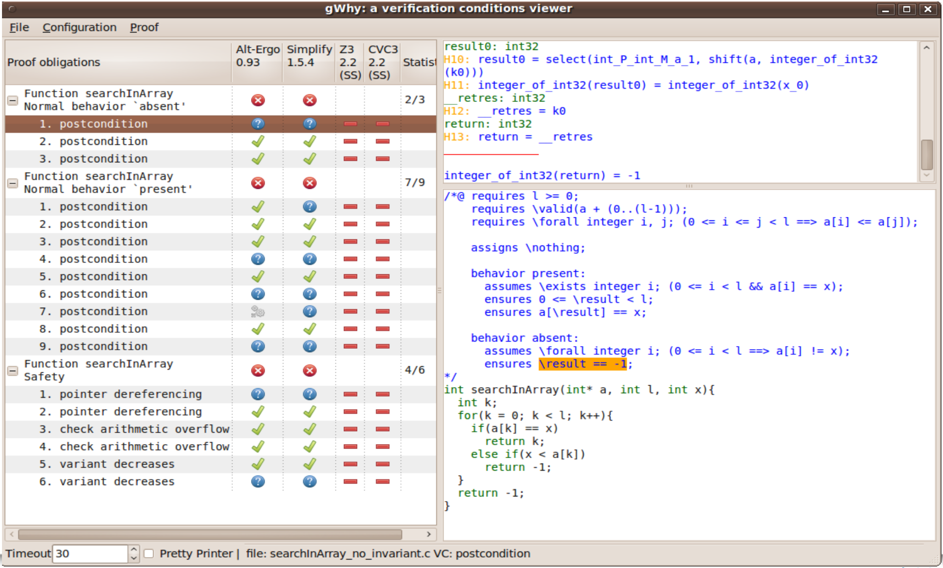

Second behavior:
If x absent in a

then returns -1

Jessie does not prove everything :



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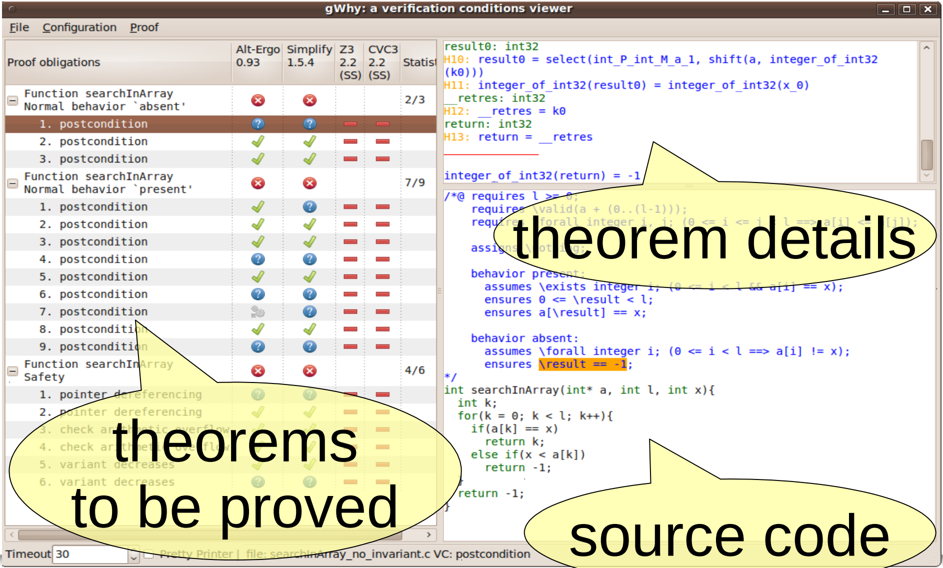

```c
/*@ requires l >= 0;
    requires \valid(a + (0..(l-1)));
    requires \forall integer i, j; (0 <= i <= j < l ==> a[i] <= a[j]);

    assigns \nothing;

    behavior present:
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*/
int searchInArray(int* a, int l, int x){
  int k;
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      return k ;  // found, returns index
    else if(x < a[k])
      return -1 ; // not found (a sorted)
  }
  return -1 ;     // not found
}
```

```
/*@ requires l >= 0;
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    requires \forall integer i, j; (0 <= i <= j < l ==> a[i] <= a[j]);

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    behavior present:
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      ensures 0 <= \result < l;
      ensures a[\result] == x;

    behavior absent:
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      ensures \result == -1;
*/
int searchInArray(int* a, int l, int x){
  int k;
  for(k = 0; k < l; k++){
    if(a[k] == x)
      return k ;   // found, returns index
    else if(x < a[k])
      return -1 ; // not found (a sorted)
  }
  return -1 ;      // not found
}
```

Difficulty: unknown number of loop iterations

Solution : Specify loop properties

```
/*@ ...
*/
int searchInArray(int* a, int l, int x){
  int k;
  /*@ loop invariant 0 <= k <= l &&
         \forall integer i; 0 <= i < k ==> a[i] < x;
      loop assigns \nothing;
      loop variant l-k;
  */
  for(k = 0; k < l; k++){
    if(a[k] == x)
      return k ;  // found, returns index
    else if(x < a[k])
      return -1 ; // not found (a sorted)
  }
  return -1 ;     // not found
}
```

Solution : Specify loop properties

invariant: holds after k iterations

```
/*@ ...
*/
int searchInArray(int* a, int l, int x){
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  /*@ loop invariant 0 <= k <= l &&
          \forall integer i; 0 <= i < k ==> a[i] < x;
        loop assigns \nothing;
        loop variant l-k;
  */
  for(k = 0; k < l; k++){
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      return k ;  // found, returns index
    else if(x < a[k])
      return -1 ; // not found (a sorted)
  }
  return -1 ;     // not found
}
```

Solution : Specify loop properties

invariant: holds after k iterations

does not assign variables

```
/*@ ...
*/
int searchInArray(int* a, int l, int x){
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         \forall integer i; 0 <= i < k ==> a[i] < x;
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      loop variant l-k;
  */
  for(k = 0; k < l; k++){
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      return k ;  // found, returns index
    else if(x < a[k])
      return -1 ; // not found (a sorted)
  }
  return -1 ;     // not found
}
```

Solution : Specify loop properties

```
/*@ ...
*/
int searchInArray(int* a, int l, int x){
  int k;
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      loop assigns \nothing;
      loop variant l-k;
  */
  for(k = 0; k < l; k++){
    if(a[k] == x)
      return k ;   // found, returns index
    else if(x < a[k])
      return -1 ;  // not found (a sorted)
  }
  return -1 ;      // not found
}
```

invariant: holds after k iterations

does not assign variables

variant: ≤ l−k more iterations

```c
/*@ requires l >= 0;
    requires \valid(a + (0..(l-1)));
    requires \forall integer i, j; (0 <= i <= j < l ==> a[i] <= a[j]);

    assigns \nothing;

    behavior present:
      assumes \exists integer i; (0 <= i < l && a[i] == x);
      ensures 0 <= \result < l;
      ensures a[\result] == x;

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      assumes \forall integer i; (0 <= i < l ==> a[i] != x);
      ensures \result == -1;
*/
int searchInArray(int* a, int l, int x){
  int k;
  /*@ loop invariant 0 <= k <= l &&
        \forall integer i; 0 <= i < k ==> a[i] < x;
      loop assigns \nothing;
      loop variant l-k;
  */
  for(k = 0; k < l; k++){
    if(a[k] == x)
      return k ;  // found, returns index
    else if(x < a[k])
      return -1 ; // not found (a sorted)
  }
  return -1 ;     // not found
}
```
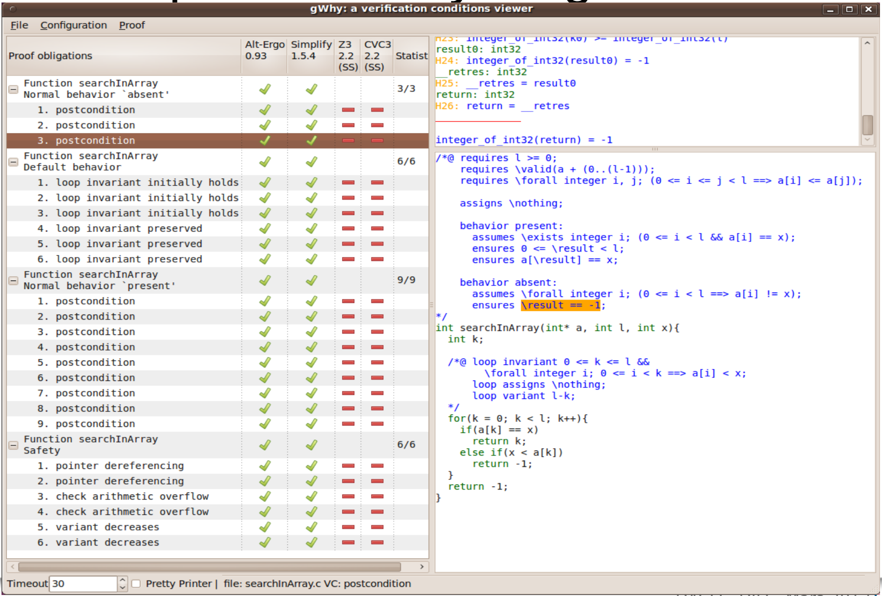

Jessie proves everything now !



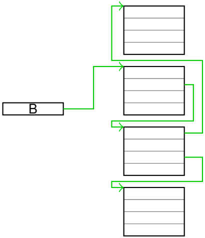
Plan

MMU: hardware mechanism for memory protection

- Splits memory into same-size *pages*
- Virtual memory roles:
  - Memory organization
  - Memory protection

➜ Hardware mechanism to restrict writing to a page: a page *p* is accessible iff:

1. The special register *B* points to a page *pd*,
2. That points to a page *pt*
3. That points to *p* (i.e. *p* is at level 3)



P_0 (accessible data)

P_1 (used as page directory)

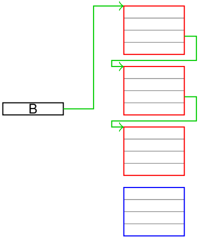
P_2 (used as page table)

P_3 (accessible data)

- Hypervisor must control what is written to page tables and directories

Hypervisor algorithm for memory isolation (1)

- Concept of *types* (PD,PT,D)
  - **Rule:** Pages may only be used according to their respective types
  - **Rule:** Pages of type PT and PD may only be changed by the hypervisor
- Dynamic usage of resources make attacks possible:
  - $\rightarrow$ change of type
  - A possible attack : a “data” page changes to type “PT”, then is used as a page table



P_0 (type PD, used as page directory)

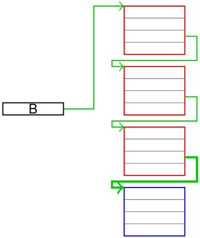
P_1 (type PT, used as page table)

P_2 (type D, accessible data)

P_3 (not owned, not accessible)

Hypervisor algorithm for memory isolation (1)

- Concept of *types* (PD,PT,D)
  - **Rule:** Pages may only be used according to their respective types
  - **Rule:** Pages of type PT and PD may only be changed by the hypervisor
- Dynamic usage of resources make attacks possible:
  - $\rightarrow$ change of type
  - A possible attack : a “data” page changes to type “PT”, then is used as a page table



P_0 (type PD, used as page directory)

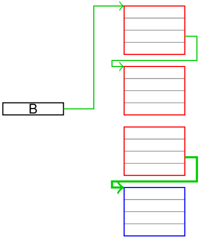
P_1 (type PT, used as page table)

P_2 (type D, accessible data)

P_3 (not owned, not accessible)

Hypervisor algorithm for memory isolation (1)

- Concept of *types* (PD,PT,D)
  - **Rule:** Pages may only be used according to their respective types
  - **Rule:** Pages of type PT and PD may only be changed by the hypervisor
- Dynamic usage of resources make attacks possible:
  - $\rightarrow$ change of type
  - A possible attack : a "data" page changes to type "PT", then is used as a page table



P_0 (type PD, used as page directory)

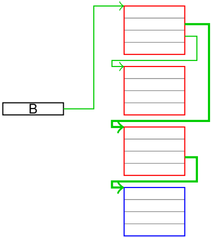
P_1 (type PT, used as page table)

P_2 (type PT, unused)

P_3 (not owned, not accessible)

Hypervisor algorithm for memory isolation (1)

- Concept of *types* (PD,PT,D)
  - **Rule:** Pages may only be used according to their respective types
  - **Rule:** Pages of type PT and PD may only be changed by the hypervisor
- Dynamic usage of resources make attacks possible:
  - $\rightarrow$ change of type
  - A possible attack : a “data” page changes to type “PT”, then is used as a page table



P_0 (type PD, used as page directory)

P_1 (type PT, used as page table)

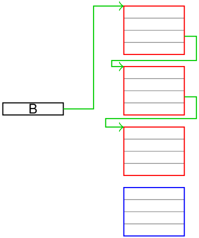
P_2 (type PT, used as page table)

P_3 (not owned, accessible data)

- Counter-measure: changing type requires “cleanup”

Hypervisor algorithm for memory isolation (2)

- Insufficient counter-measure
- Other attack: pages used both as “data” (accessibles) and “pagetable”.



P_0 (type PD, used as page directory)

P_1 (type PT, used as page table)

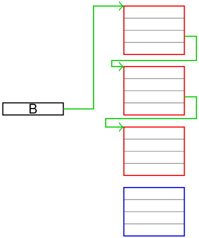
P_2 (type D, accessible data)

P_3 (not owned, not accessible)

- Possible attack: a page used as “data”, change type to “PT” (with cleanup), used as pagetable, then directly changed

Hypervisor algorithm for memory isolation (2)

- Insufficient counter-measure
- Other attack: pages used both as “data” (accessibles) and “pagetable”.



P_0 (type PD, used as page directory)

P_1 (type PT, used as page table)

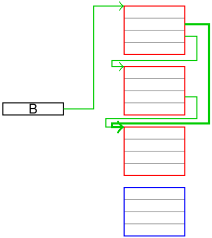
P_2 (type PT, accessible data)

P_3 (not owned, not accessible)

  - Possible attack: a page used as “data”, change type to “PT” (with cleanup), used as pagetable, then directly changed

Hypervisor algorithm for memory isolation (2)

- Insufficient counter-measure
- Other attack: pages used both as “data” (accessibles) and “pagetable”.



P_0 (type PD, used as page directory)

P_1 (type PT, used as page table)

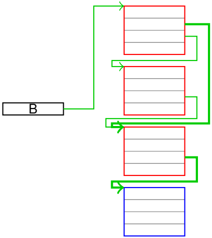
P_2 (type PT, accessible data, used as page table)

P_3 (not owned, not accessible)

- Possible attack: a page used as “data”, change type to “PT” (with cleanup), used as pagetable, then directly changed

Hypervisor algorithm for memory isolation (2)

- Insufficient counter-measure
- Other attack: pages used both as “data” (accessibles) and “pagetable”.



P_0 (type PD, used as page directory)

P_1 (type PT, used as page table)

P_2 (type PT, accessible data, used as page table)

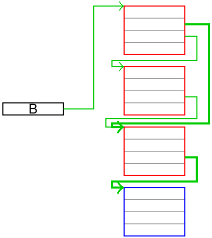
P_3 (not owned, accessible data)

- Possible attack: a page used as “data”, change type to “PT” (with cleanup), used as pagetable, then directly changed
- Counter-measure:
  - Account for number of mappings to a page
  - Allow changing types only if number of mappings = 0

- Is it still possible to break the **Rules**?

Hypervisor algorithm for memory isolation (2)

- Insufficient counter-measure
- Other attack: pages used both as “data” (accessibles) and “pagetable”.



P_0 (type PD, used as page directory)

P_1 (type PT, used as page table)

P_2 (type PT, accessible data, used as page table)

P_3 (not owned, accessible data)

  - Possible attack: a page used as “data”, change type to “PT” (with cleanup), used as pagetable, then directly changed
  - Counter-measure:
    - Account for number of mappings to a page
    - Allow changing types only if number of mappings = 0

- Is it still possible to break the **Rules**?

➜ No (formally proved)

Verification of Virtual Memory Module

- We specify a module prototype and prove it in Frama-C / Jessie

What to do with proof failures ?

- Proof failures come from complex inductive predicates
- They can be proved interactively in Coq (long, expensive)
- Or...

```
/*@ inductive MappingsAllOverOnePage{L}(integer pageIndex, integer lastIndex, integer refferredIndex, integer mappingsNum){
  @   case oneEq:
  @     \forall integer pageIndex, refferredIndex;
  @       0<=pageIndex<NumOfPages && 0<=refferredIndex<NumOfPages && pContents[pageIndex*PageSizeWords] == refferredIndex ==>
  @       MappingsAllOverOnePage(pageIndex, 0, refferredIndex, 1);

  @   case oneNotEq:
  @     \forall integer pageIndex, refferredIndex;
  @       0<=pageIndex<NumOfPages && 0<=refferredIndex<NumOfPages && pContents[pageIndex*PageSizeWords] != refferredIndex  ==>
  @       MappingsAllOverOnePage(pageIndex, 0, refferredIndex, 0);

  @   case severalLastNotEq:
  @     \forall integer pageIndex, lastIndex, refferredIndex, mappingsNum;
  @       (0<=pageIndex<NumOfPages && 0<=refferredIndex<NumOfPages && 0 < lastIndex < PageSizeWords &&
  @       mappingsNum >=0 && pContents[pageIndex*PageSizeWords + lastIndex] != refferredIndex &&
  @       MappingsAllOverOnePage(pageIndex, lastIndex-1, refferredIndex, mappingsNum) ==>
  @       MappingsAllOverOnePage(pageIndex, lastIndex, refferredIndex, mappingsNum) );

  @   case severalLastEq:
  @     \forall integer pageIndex, lastIndex, refferredIndex, mappingsNum;
  @       (0<=pageIndex<NumOfPages && 0<=refferredIndex<NumOfPages && 0 < lastIndex < PageSizeWords &&
  @       mappingsNum >=0 && pContents[pageIndex*PageSizeWords + lastIndex] == refferredIndex &&
  @       MappingsAllOverOnePage(pageIndex, lastIndex-1, refferredIndex, mappingsNum) ==>
  @       MappingsAllOverOnePage(pageIndex, lastIndex, refferredIndex, mappingsNum+1) );
  @ }
  @
  @ inductive MappingsAllOverAllPages{L}(integer lastPage, integer refferredIndex, integer mappingsNum){
  @   case onePage:
  @     \forall integer refferredIndex, mappingsNum;
          ( 0<=refferredIndex<NumOfPages &&
  @       MappingsAllOverOnePage(0, PageSizeWords-1, refferredIndex, mappingsNum) ) ==>
  @       MappingsAllOverAllPages(0, refferredIndex, mappingsNum);
  @   case severalPages:
  @     \forall integer lastPage, refferredIndex, mappingsNumPrevPages, mappingsNumLastPage;
  @       ( 0<=refferredIndex<NumOfPages && 0 < lastPage < NumOfPages ==>
  @       MappingsAllOverAllPages(lastPage-1, refferredIndex, mappingsNumPrevPages) &&
  @       MappingsAllOverOnePage(lastPage, PageSizeWords-1, refferredIndex, mappingsNumLastPage) ==>
  @       MappingsAllOverAllPages(lastPage, refferredIndex, mappingsNumPrevPages+mappingsNumLastPage) );
  @ }
*/
```

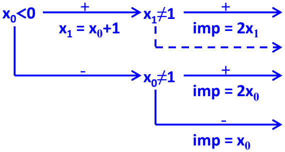
Testing to complete the proof

- Isolate unproved parts in the smallest possible functions
- Write (automatically generate with E-ACSL) C specification : pre/post
- Use cross-checking to verify conformity
  - Exhaustive path exploration, and even more :
  - (Function paths) X (Spec paths)
- If necessary, reduce search space
  - Consider a smaller number of pages
  - Consider a smaller page size

PathCrawler testing tool

- Concolic /DSE testing tool for C developed at CEA LIST
- Input: a complete compilable source code
- Automatically creates test cases to cover program paths
- Uses code instrumentation, concrete and symbolic execution, constraint solving
- Exact semantics: don't rely on concrete values to approximate the path predicate
- Similar to PEX, DART/CUTE, KLEE, SAGE etc.

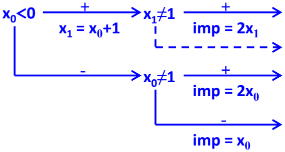
Cross-checking conformity with a specification



implementation

```
int f(int x){
 if(x < 0)
  x = x + 1;
 if(x != 1)
  x = 2*x;
 return x; }
```

Cross-checking conformity with a specification



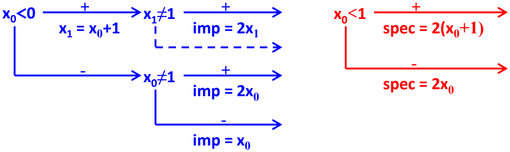
implementation

```
int f(int x){
 if(x < 0)
  x = x + 1;
 if(x != 1)
  x = 2*x;
 return x; }
```

specification

If x is less than 1 then
the result should be 2(x + 1)
else the result should be 2x

Cross-checking conformity with a specification



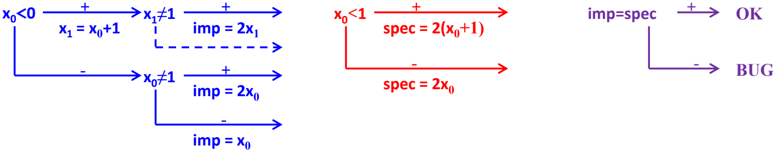
implementation

```
int f(int x){
 if(x < 0)
  x = x + 1;
 if(x != 1)
  x = 2*x;
 return x; }
```

specification

```
int spec_f(int x){
 if(x < 1)
  x = 2*(x + 1);
 else
  x = 2*x;
 return x; }
```

Cross-checking conformity with a specification



implementation

```
int f(int x){
 if(x < 0)
  x = x + 1;
 if(x != 1)
  x = 2*x;
 return x; }
```

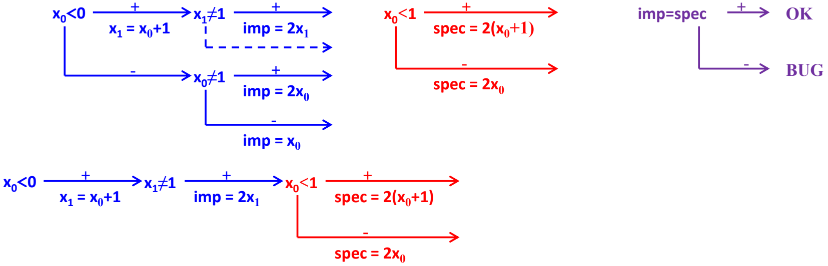
specification

```
int spec_f(int x){
 if(x < 1)
  x = 2*(x + 1);
 else
  x = 2*x;
 return x; }
```

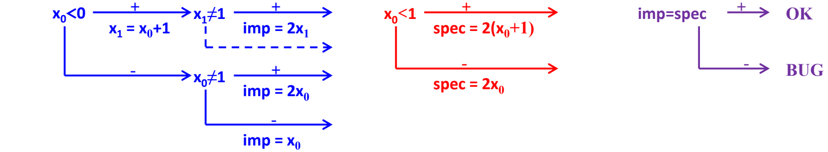
comparison

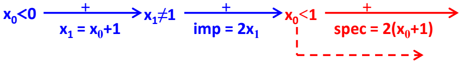
```
int cross_f(int x){
 int imp = f(x);
 int spec=spec_f(x);
 if(imp!=spec)
   return 0;
 else return 1; }
```

Cross-checking conformity with a specification



Cross-checking conformity with a specification

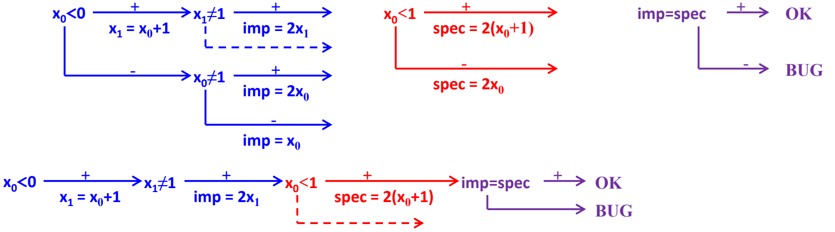




$$x_0 < 0 \wedge (x_0 + 1) \neq 1 \wedge x_0 < 1 \rightarrow x_0 < 0$$

$$x_0 < 0 \wedge (x_0 + 1) \neq 1 \wedge x_0 \geq 1$$

Cross-checking conformity with a specification



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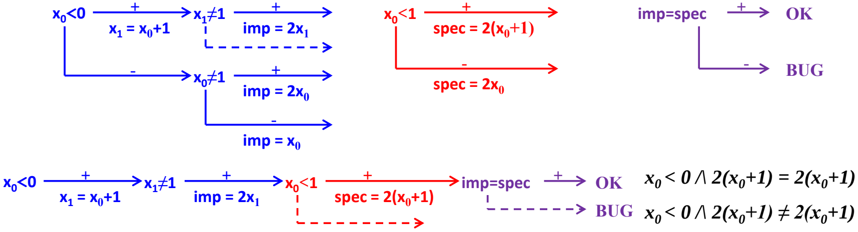
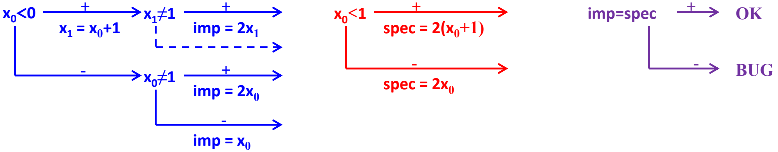
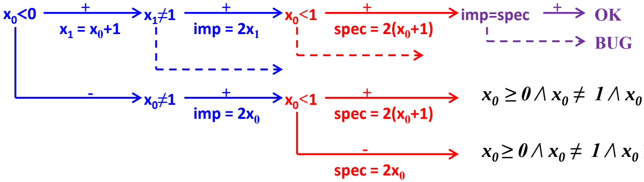


Cross-checking conformity with a specification



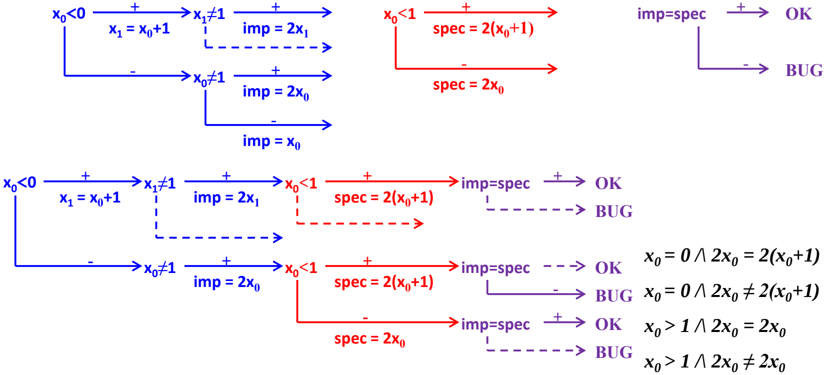


$x_0 < 0$

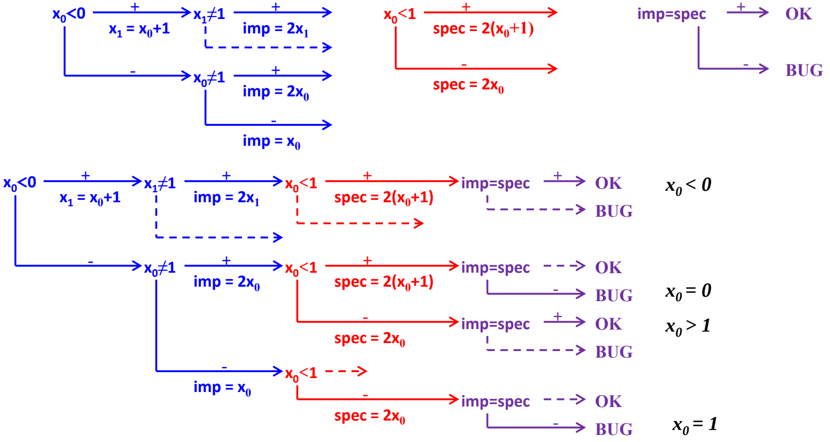
$x_0 \geq 0 \wedge x_0 \neq 1 \wedge x_0 < 1 \rightarrow x_0 = 0$

$x_0 \geq 0 \wedge x_0 \neq 1 \wedge x_0 \geq 1 \rightarrow x_0 > 1$

Cross-checking conformity with a specification



Cross-checking conformity with a specification



Proving the VM module with Frama-C: results

- Prove that all functions fulfill their specifications
- Prove that the **Rules** hold $\rightarrow$ proof of memory isolation
- Statistics:
  - 2000 LOC, 80% spec, 20% C code
  - 37 functions, 3969 properties to be proved
  - 3915 properties (98.8%) proved with Jessie
- Proof-of-concept, much work remains:
  - Modeling hardware mechanisms (e.g. TLB cache)
  - Proof of multicore version (uses lock-free algorithms)
  - Parts of the code have two versions:
    - "simple" (automatically provable)
    - "fast" (efficient, but requires more proof effort)
  - Proof of remaining 1.2% using interactive theorem prover

Plan

1. Anaxagoros: a secure hypervisor for the cloud
2. Proof of programs with Frama-C
3. Verification of a hypervisor algorithm
4. **Conclusion**

Summary

- Anaxagoros: a secure foundation for the Cloud
  - Provides maximum isolation between tasks or VMs
  - Strong focus on resource security
  - Allows reusability/ease of use through virtualization
  - Minimizes the amount of trusted code $\rightarrow$
    - minimize bugs and security breaches
    - amenable to formal verification
- Formal verification technology is becoming applicable
  - Formal proof provides the *highest* level of confidence in a program
  - Tools such as Frama-C are now able to prove actual algorithms with feasible effort
  - Requires an important effort; reasonable only if hypervisor is designed to be proved (size, cleanness of internal interfaces)
  - Other verification techniques in Frama-C applicable with less effort (test generation, abstract interpretation...)

Perspectives

- Continue improving Anaxagoros:
  - Improve performance, in particular on specific industrial cases
  - Study hardware breaches in performance isolation (e.g. cache partitioning, limitation of preemptions)
- Continue the proof effort
  - Use interactive proof assistant (Coq) for the 1.2% unproved theorems
  - On-going research efforts:
    - Proving parallel algorithms
    - Maintainability: updating the proof when the code changes
- Industrial offer with a CEA startup being created around the Frama-C technology
  - Help industry to use formal methods for cybersecurity

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