A Signature Scheme for Distributed Executions based on Macro-Dataflow Analysis

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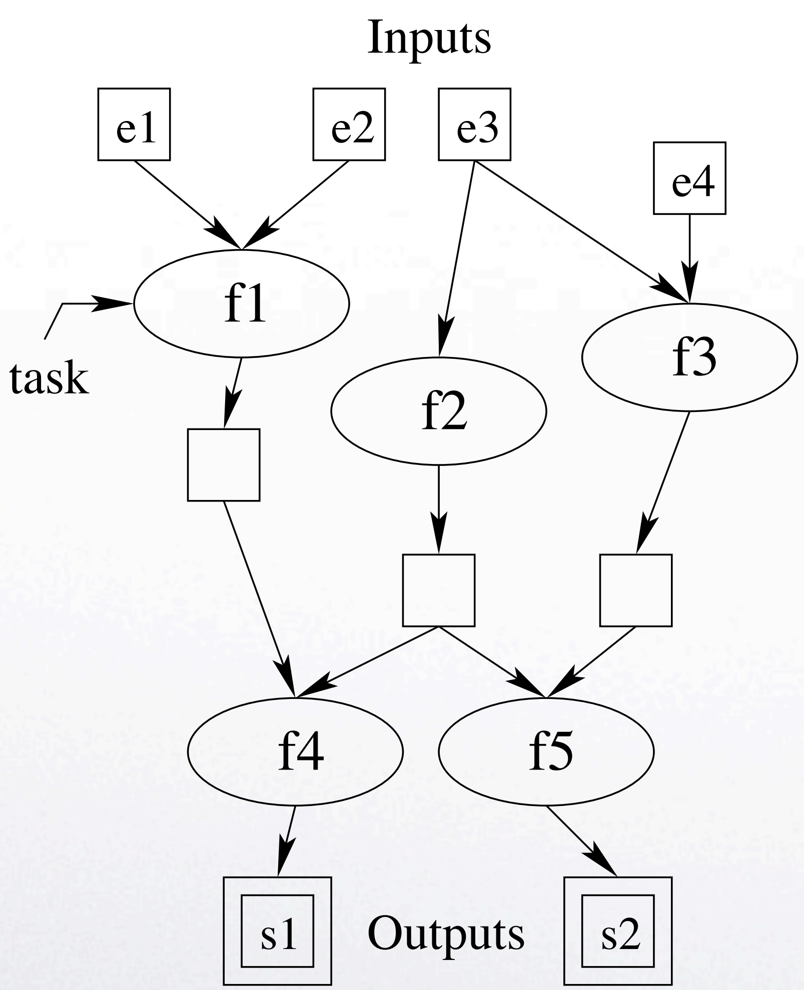
Summary

- Context & Motivation
- Related work
- Checkable Signature of distributed execution flow
  - offline fingerprint generation
  - online signature generation & verification
- Implemention & experimentations
- Conclusion

Context

- Execution over a large-scale distributed platform
  - Computing grid, desktop grid, Cloud
    - heterogeneous (processor, network ...)
    - dynamic (failures, reservations ...)
- Bad things happens
  - [D]DoS, malware, trojan horse, vulnerability exploit etc.
    - Crash, buffer overflows, machine-code injection
- Global Purpose: **ensure execution integrity**

Execution model



- [Parallel] program **P** executed over M
  - single machine, grid etc.
- Abstract representation of the distributed execution of **P**
  - Bipartite DAG $G = (\mathcal{V}, \mathcal{E})$
  - $\mathcal{V} = \mathcal{V}_t \cup \mathcal{V}_d$
- execution of T in **P** unfold *G(T)*
- the set of all *G(T)* characterize G

Distributed execution & dataflow graphs

- Permits to handle various class of fault
  - crash-fault: efficient checkpoint/rollback [CCK:BesseronGautier08]
  - cheating-fault: handle task forgery/result falsification
    - efficient detection on FJ/recursive programs [Varrette07]
    - avoid full program duplication yet costly in general
  - flow-fault: result of malicious code injection
    - general manifestation of cheating faults

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⇒ In this talk: flow-fault detection in distributed computations

Related work

- prior to a remote execution
  - Static analysis/malware fingerprint detection [Christodorecu&al.05]
  - Proof Carrying Code (PCC) [NeculaLee97]
  - Control-flow checking at the assembly level [Abel05]

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⇒ does not cover dynamic attacks in distributed environment

Related work (2)

- Control-flow integrity on sequential execution
  - Operate at the assembly level
    - include result-checking [Castro&al06]
    - with graphs (node~block) & XOR signature [Oh&al02]

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⇒ extension at middleware level to distributed computation

Fault model

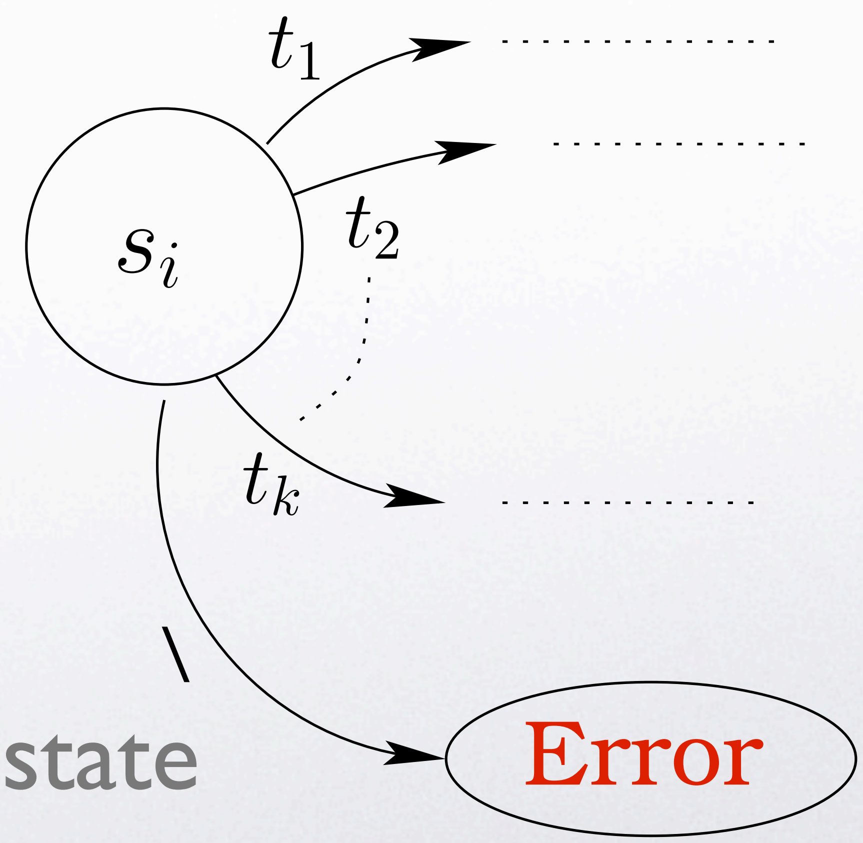
Definition 1 (Flow fault). *Let G^{ref} denotes the (reference) fault-free execution of $\boldsymbol{P}$ over M. Let G be the representation of an execution of $\boldsymbol{P}$ over M. Then G is said faulty or victim of a* flow fault *if the graphs G and G^{ref} differs* i.e. $G \cap G^{ref} \neq \emptyset$. *Otherwise, G is said correct.*

2 phases approach:

1. Offline fingerprint (reference signature) generation
2. Online signature generation & verification

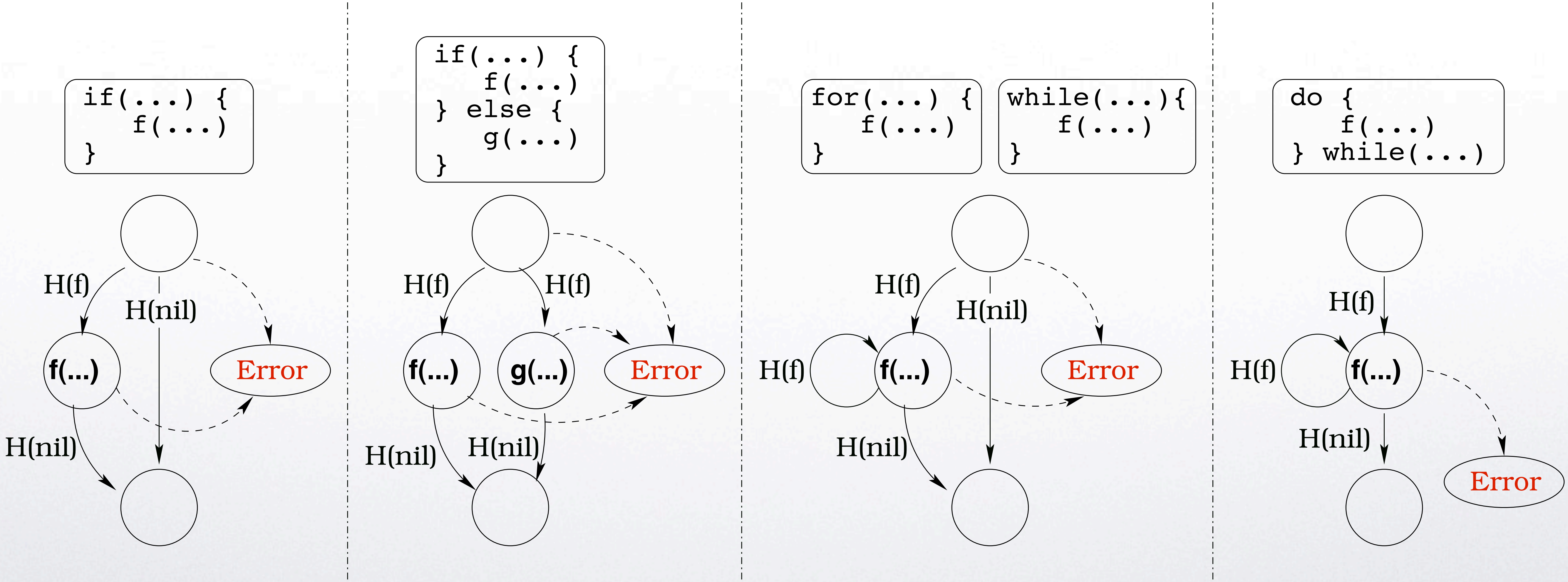
Offline fingerprint

- Based on source code analysis (C/C++) (extends CFG)
- For each task T (~function): build a NFA $\mathcal{A}_T$
  - Path `Begin`→`End` = valid flow
  - state = sub-task called in T
  - transition $s_i \rightarrow s_j$ = t_j = $H(s_j)$
    - derived from the graph unfold
    - Special transition H(nil)
    - implicit transition '\' to the `Error` state



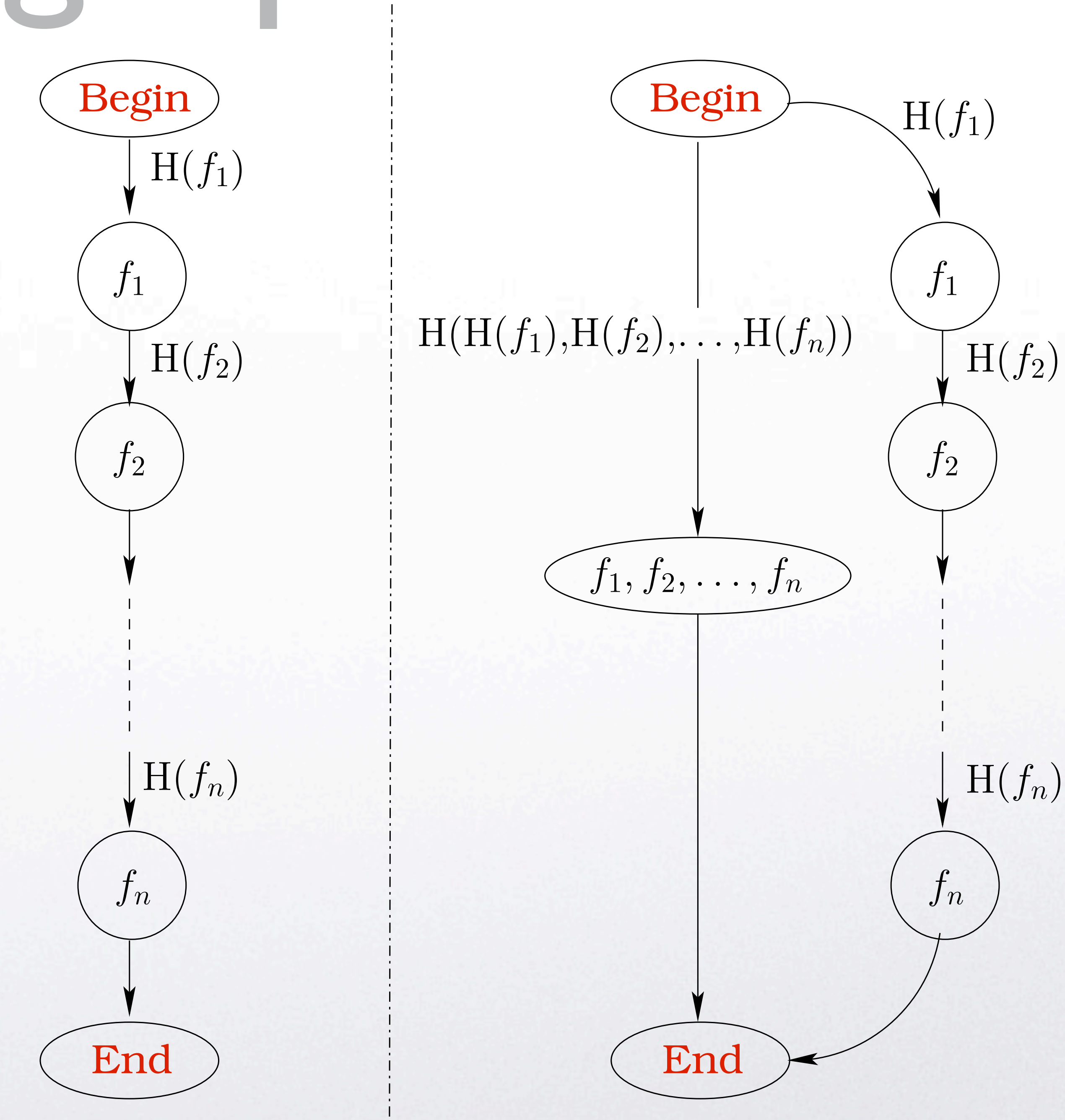
Offline fingerprint

- Structure of control impact on the fingerprint



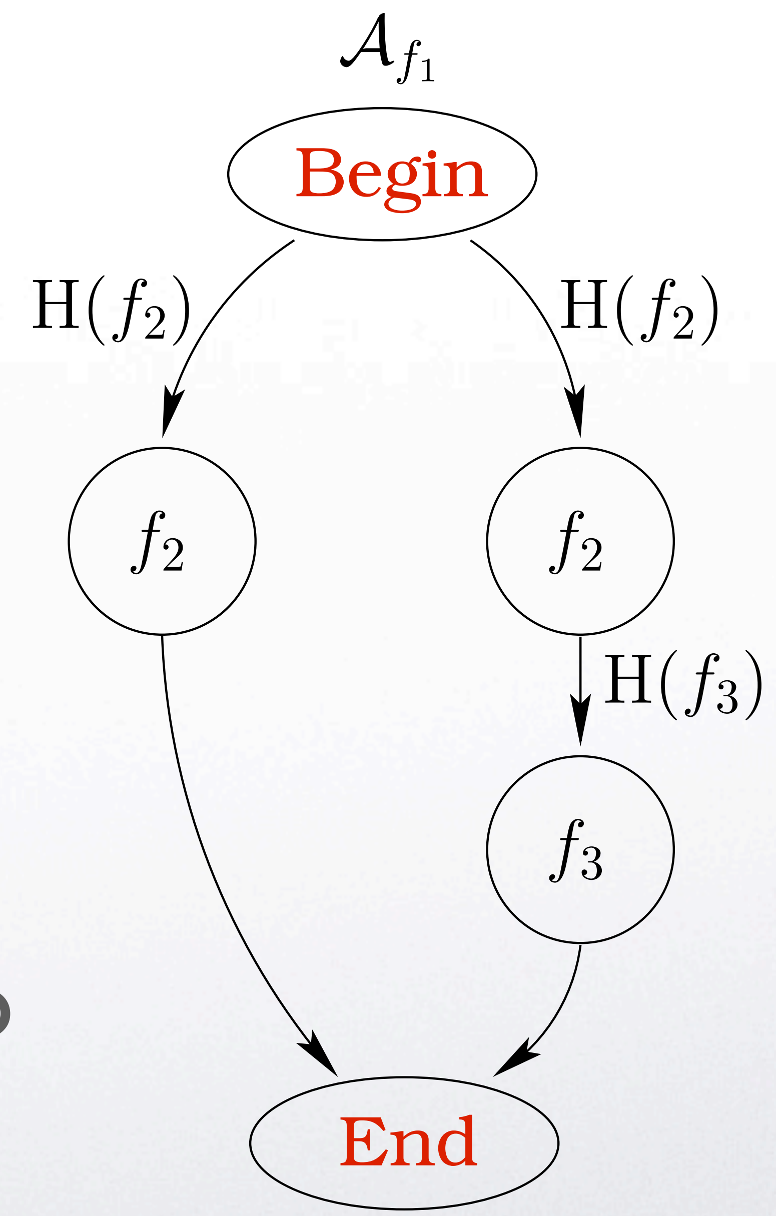
Offline fingerprint

- Once all A_T are generated:
- **optimization phase**
  - accelerate future online verification for long path
  - transition values derived from intermediate values
  - not mandatory



Fingerprint example

```
void f1 (int n) {
   if (...)  {
      f2(n) ;
      return;
   }
   f2(n−2);
   f3 ();
}
```



- Demonstrate the non-deterministic aspect of $\mathcal{A}_{f_1}$
  - conflict handled as GLR parser do
- No optimization operated here

Hash value construction

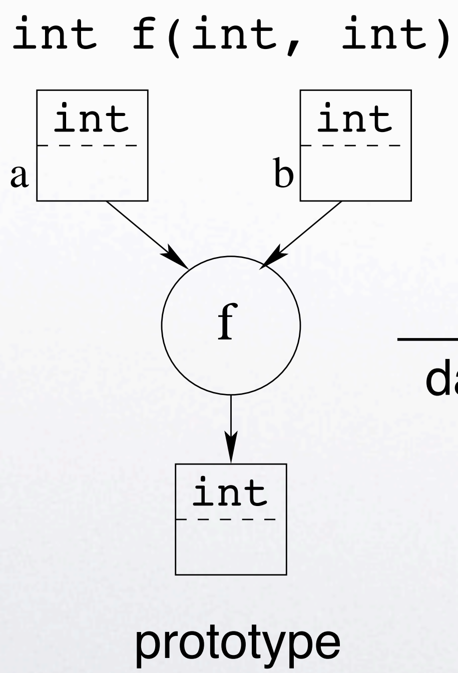
Definition 2 (Flow hash). *Let G represents an execution of $\boldsymbol{P}$ over M. Let $T \in \mathcal{V}_t$. The* flow hash *associated to the execution of T is defined by*

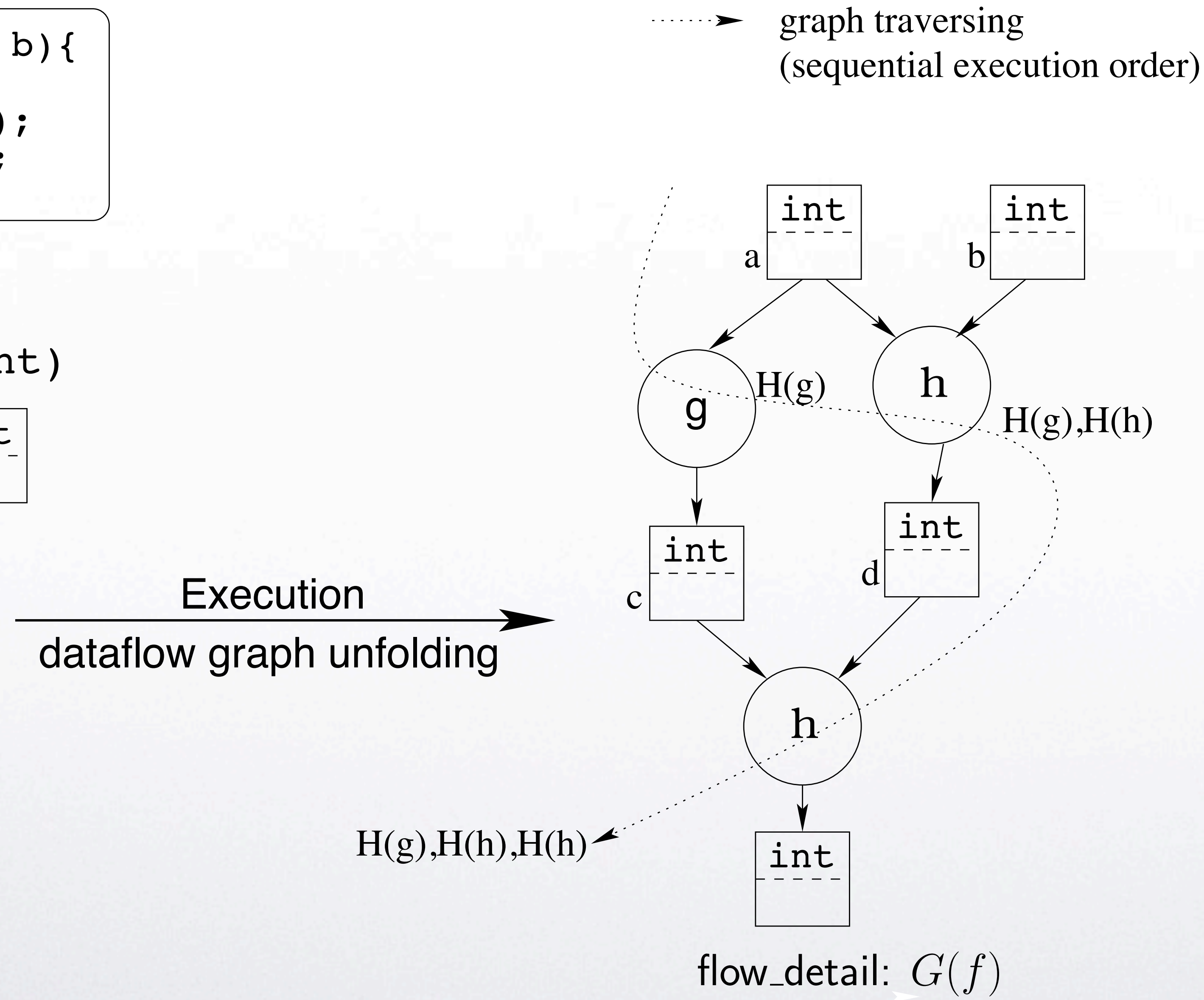
$$H(T) = (prototype, flow\_detail)$$

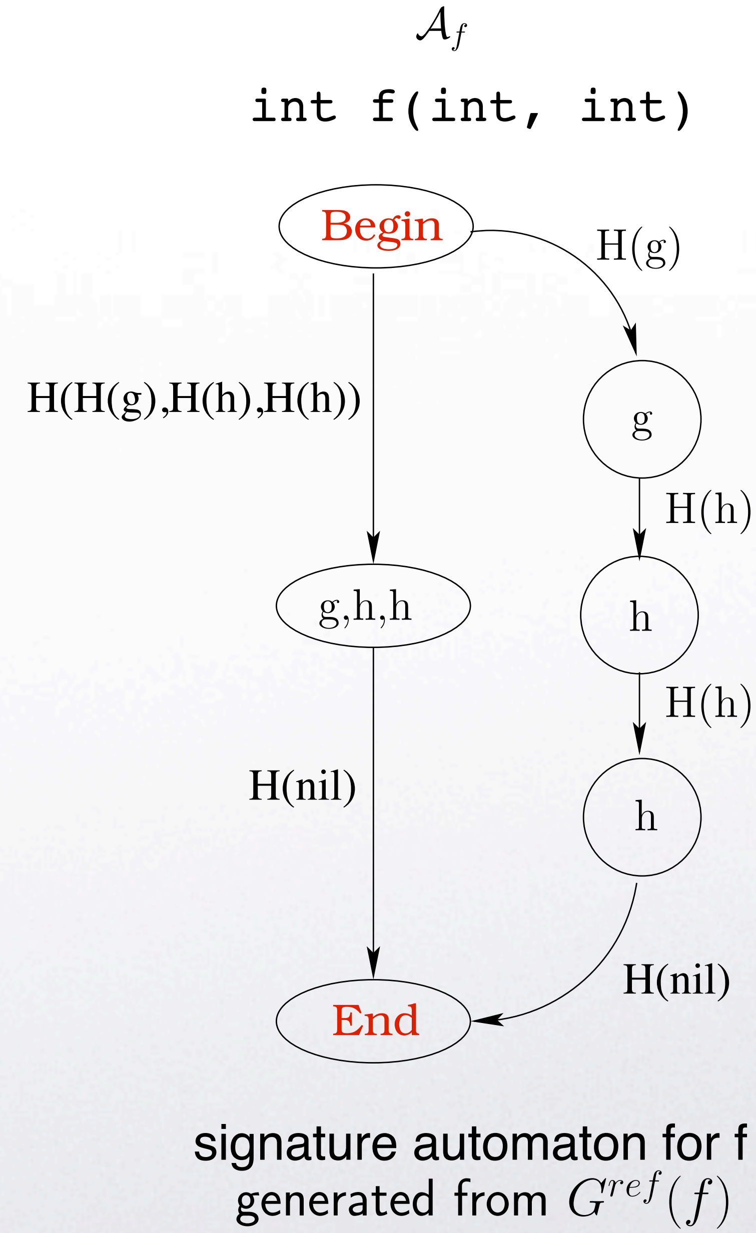
- *prototype*: function signature (C sense)
  - Ex: see `__PRETTY_FUNCTION__`
- *flow_detail*: summary of the execution flow of T
  - data-flow graph unfolded at execution of T
  - should correspond to $G^{ref}(T)$

Dynamic hash building

```
int f(int a, int b){
   int c = g(a);
   int d = h(a,b);
   return h(c,d);
}
```







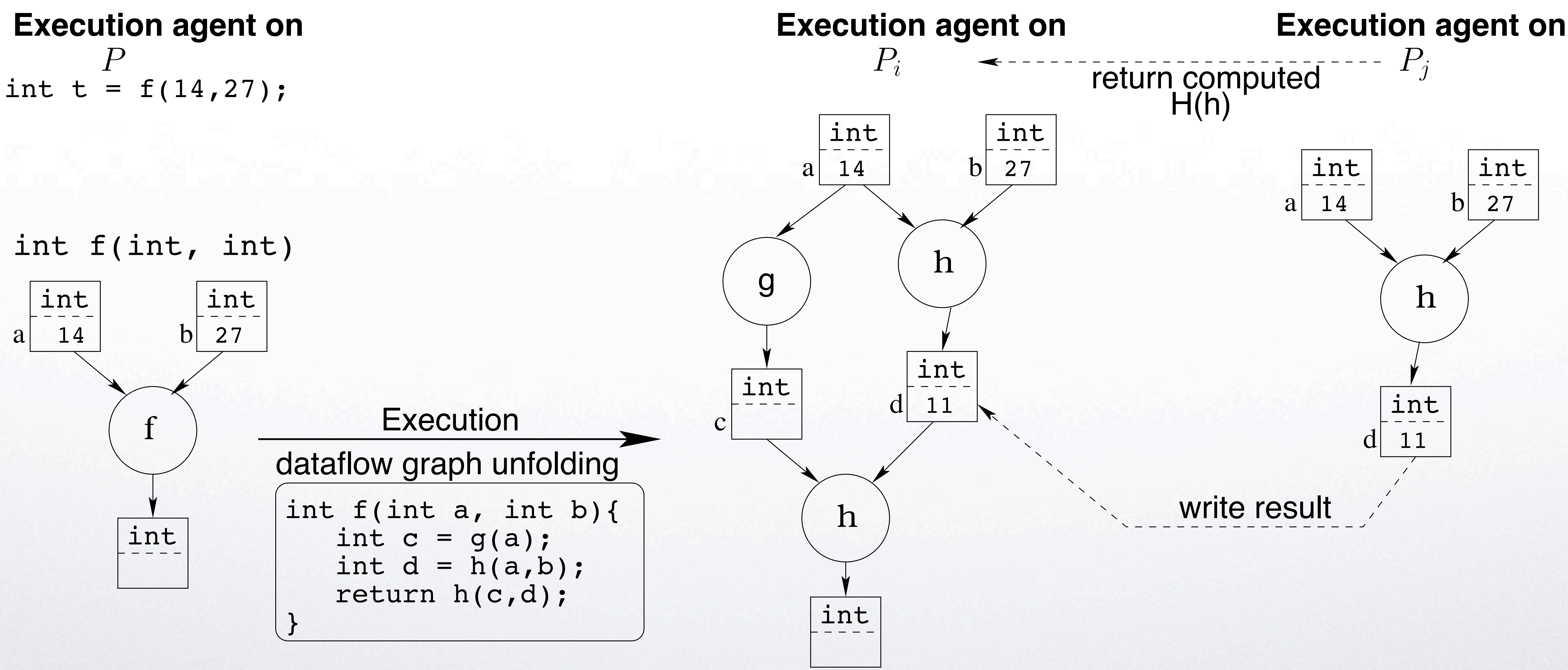
Execution engine

- **Hypothesis**: ***TRUSTABLE*** execution engine
  - dynamic construction of the macro-dataflow graph
  - online dynamic task scheduling by work stealing
  - Execution agents spread on the resources of the [distributed] computing platform

Signature verification

- Fully distributed & recursive process
  - Agent/Process P responsible to execute *f* (called in F)
  - *f* composed by sub-tasks $f_1,...,f_n$ / f_i executed on P_i
    - the P_i may be different processors
    - after execution of f_i : P_i returns $H(f_i)$ to P which check:
      - $H(f_i)$.prototype is correct (later used to feed H(f))
      - $H(f_i)$.flow_detail permits to reach state $\mathtt{End}$ in $\mathcal{A}_{f_i}$
    - after execution of all f_i and successful signature verification:
      - H(f) = [Compress]$H(f_1)$.prototype||...||$H(f_n)$.prototype

Signature verification illustrated



Verification process properties

Proposition 1. *As soon as the execution of the program* $\boldsymbol{P}$ *ends, the verification process ends in a finite time.*

Proposition 2. *Let* G^{ref} *denotes the (reference) fault-free execution of* $\boldsymbol{P}$ *over* M. *Let* $\{\mathcal{A}_{T_1}, \ldots, \mathcal{A}_{T_n}\}$ *denotes the set of automaton signatures elaborated from the analysis of* $\boldsymbol{P}$*'s source code. Let* G *be the representation of an execution of* $\boldsymbol{P}$ *over* M. *Then* G *is faulty* $\iff \exists i \in [1, n]$ *such that the verification process of the automaton signature* $\mathcal{A}_{T_i}$ *ends in the* $\mathtt{Error}$ *state.*

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⇒ any flow fault is detected **assuming** trustable agents

Implementation

- Based on Kaapi http://kaapi.gforge.inria.fr
  - C++ middleware library for distributed computing
  - Build dynamic macro-dataflow graph
  - High level interface with global address space
    - Data (`Shared<...>`): declares an object in the global space
    - Tasks (`Fork<...>`): declares a new [concurrent] task
    - Access mode given by the task (read, write, exclusive etc.)

Athapascan interface of Kaapi

```
#include <athapascan-1>

int Fiboseq(int n); // Sequential version

void Sum(Shared_w<int> res, Shared_r<int> res1, Shared_r<int> res2) { res = res1+res2; }

void Fibo( Shared_w<int> res, int n, int threshold int n) {
    if (n < threshold)
        res = Fiboseq(n);
    else {
        Shared<int> res1;
        Shared<int> res2;
        /* the Fork keyword is used to spawn new task */
        Fork<Fibo>(res1, n-1, threshold);
        Fork<Fibo>(res2, n-2, threshold );
        Fork<Sum>(res, res1, res2);
    }
}
```

Offline fingerprint generator

- Permit to generate the NFA $\mathcal{A}_T$ $\forall$T in **P**
- Analyse Kaapi source code
  - exploit preprocessed code by GCC
  - C++ parser Elsa & Generalized LR parser Elkhound
  - NFA stored encrypted in DOT format
  - decrypted at runtime for signature verification

Offline fingerprint in action

```
int main() {
    ...
    for (int i=0; i < MAX; i++)
        Fork<Fibo>(res, n, threshold);
    ...
}
```

```
#include <athapascan-1>

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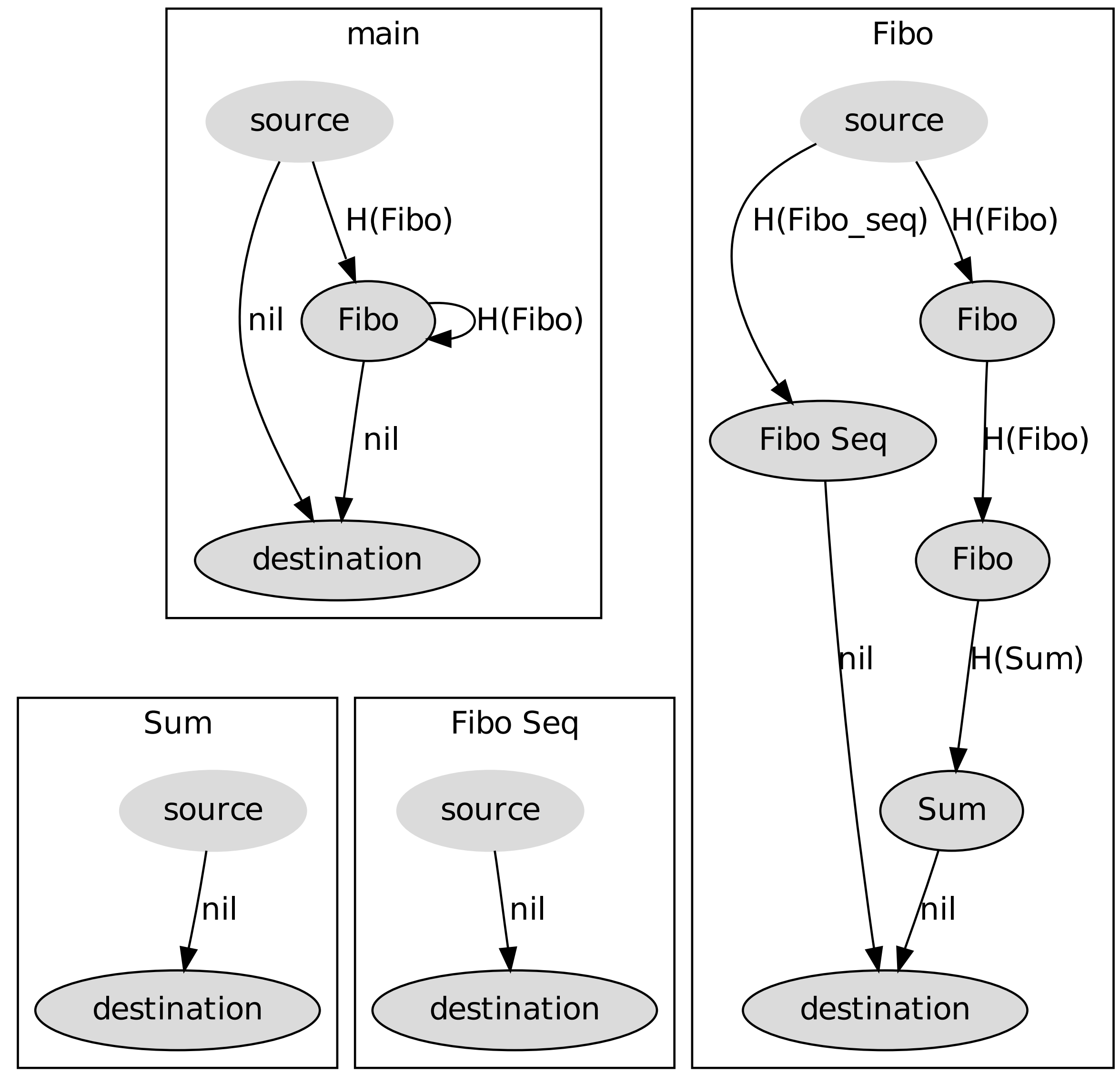
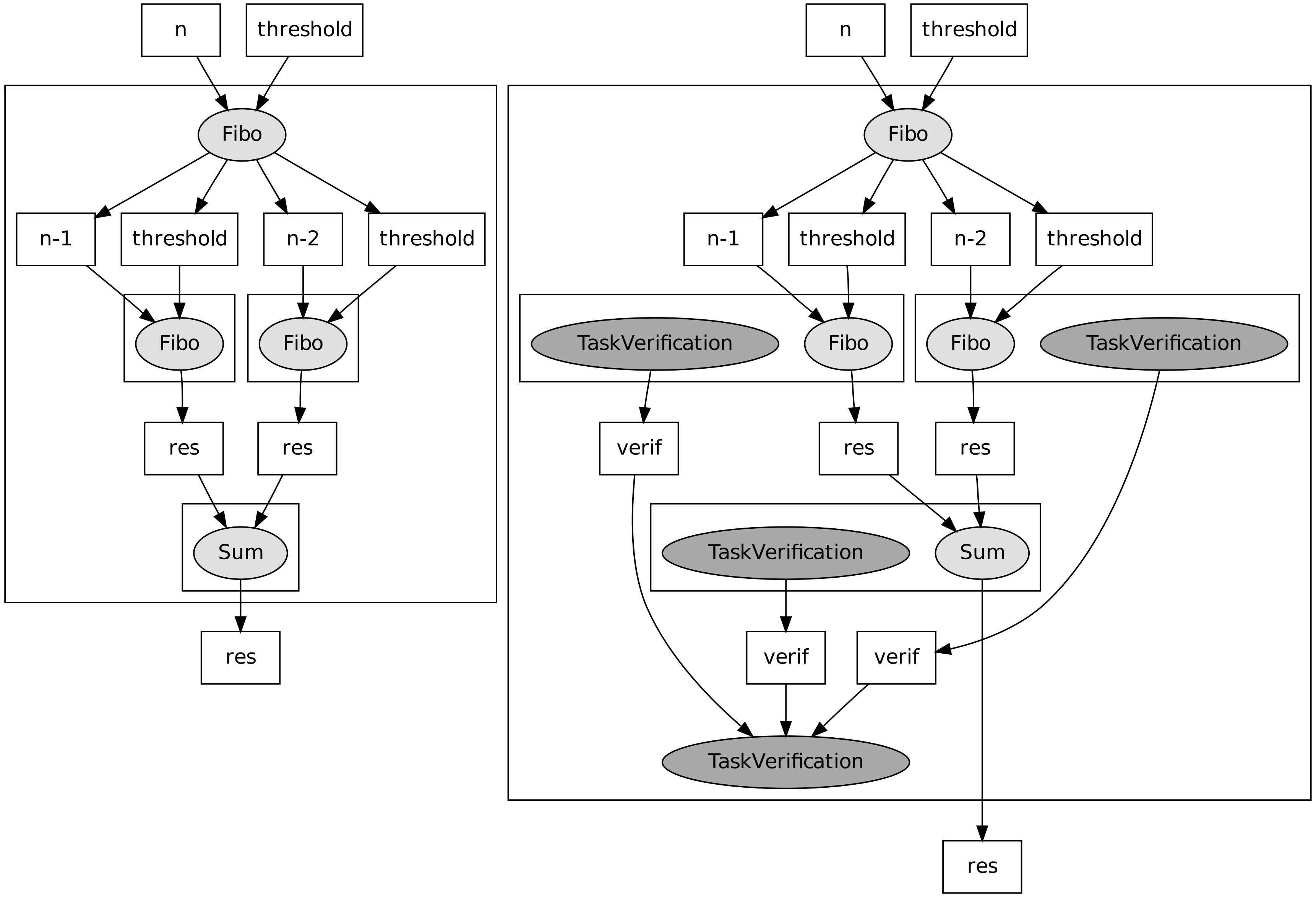


Online signature verification

- Add a new internal task to Kaapi execution engine
  - `TaskVerification` - responsible to:
    - check sub-tasks execution flow (using associated NFAs)
    - build the hash (in the `verif` shared data) to be returned to the mother task handler
- **Fully transparent to the user**
  - extension of the middleware library

Online signature verification

- Affect the data-flow graph unfolded
  - Example:



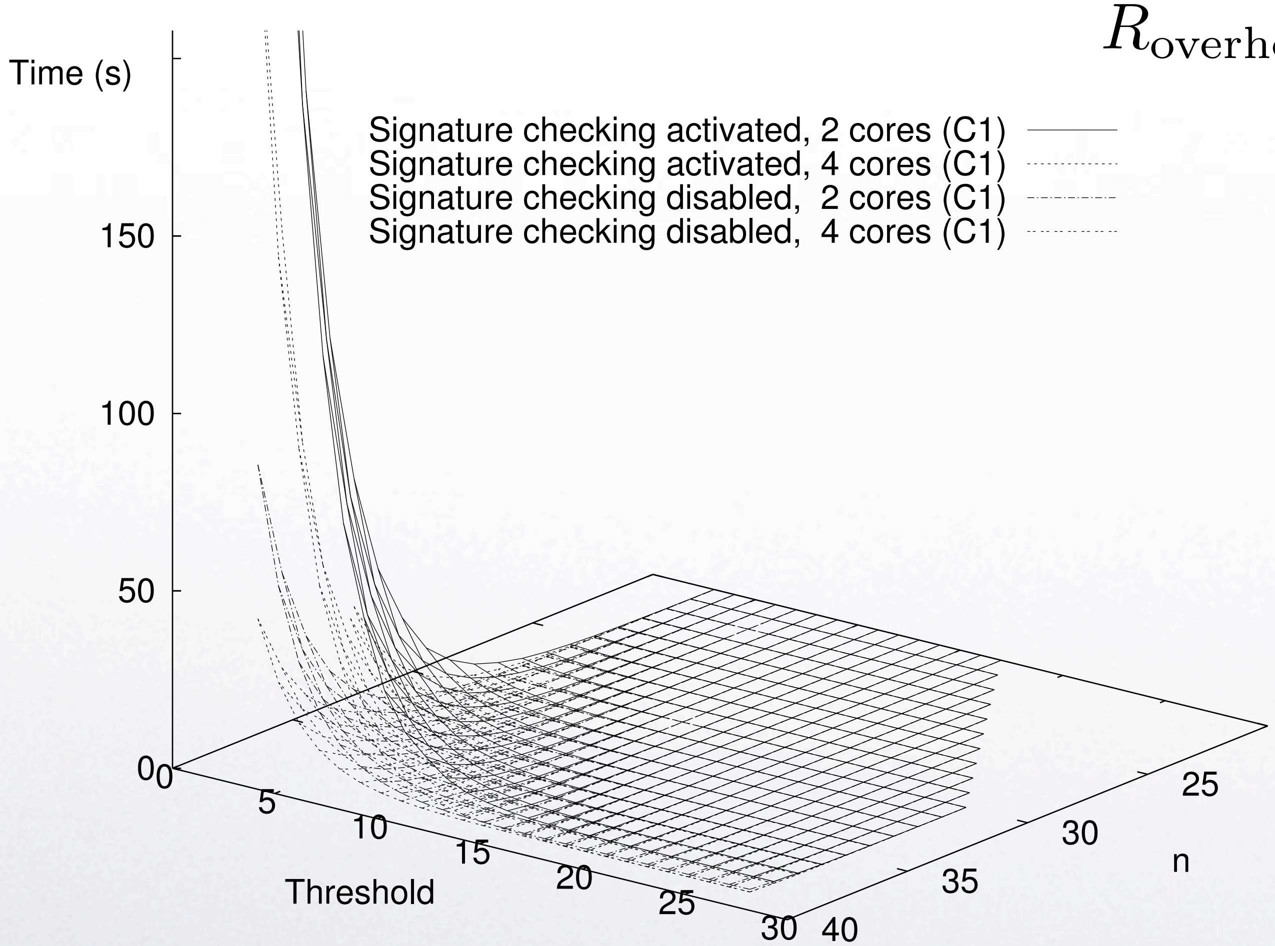
Experimental validation

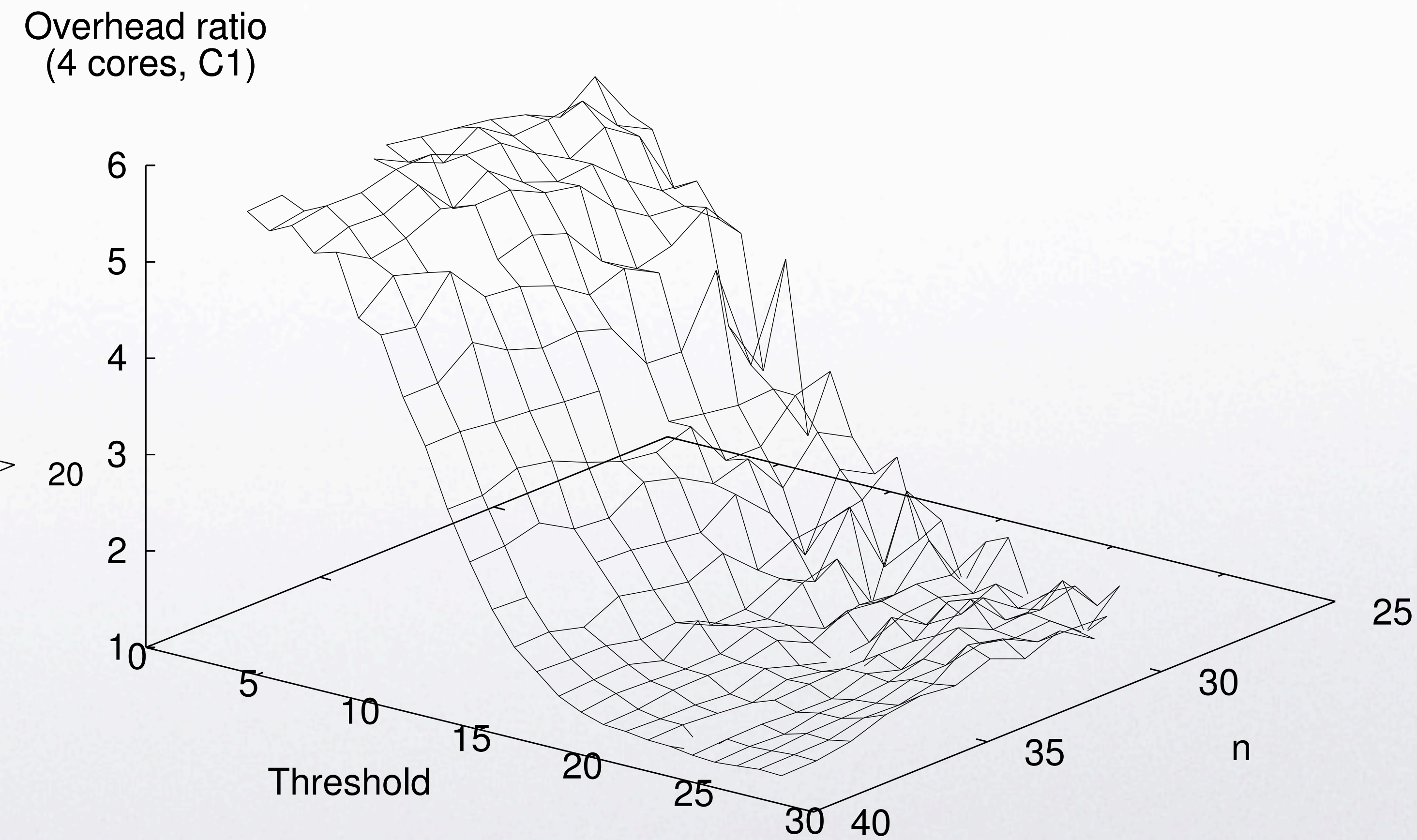
- Validation on one of the clusters of UL
  - 16 computing nodes, Intel Dual Core 3.2Ghz, 4G RAM
- Two applications evaluated:

1. Naive fibonacci
   - illustrate massive task creation (worst case for us)
   - granularity controlled by the `threshold` parameter
2. N-Queens
   - parallel implementation based on sequential code by Takaken

Experiments #1: Fibo(39)

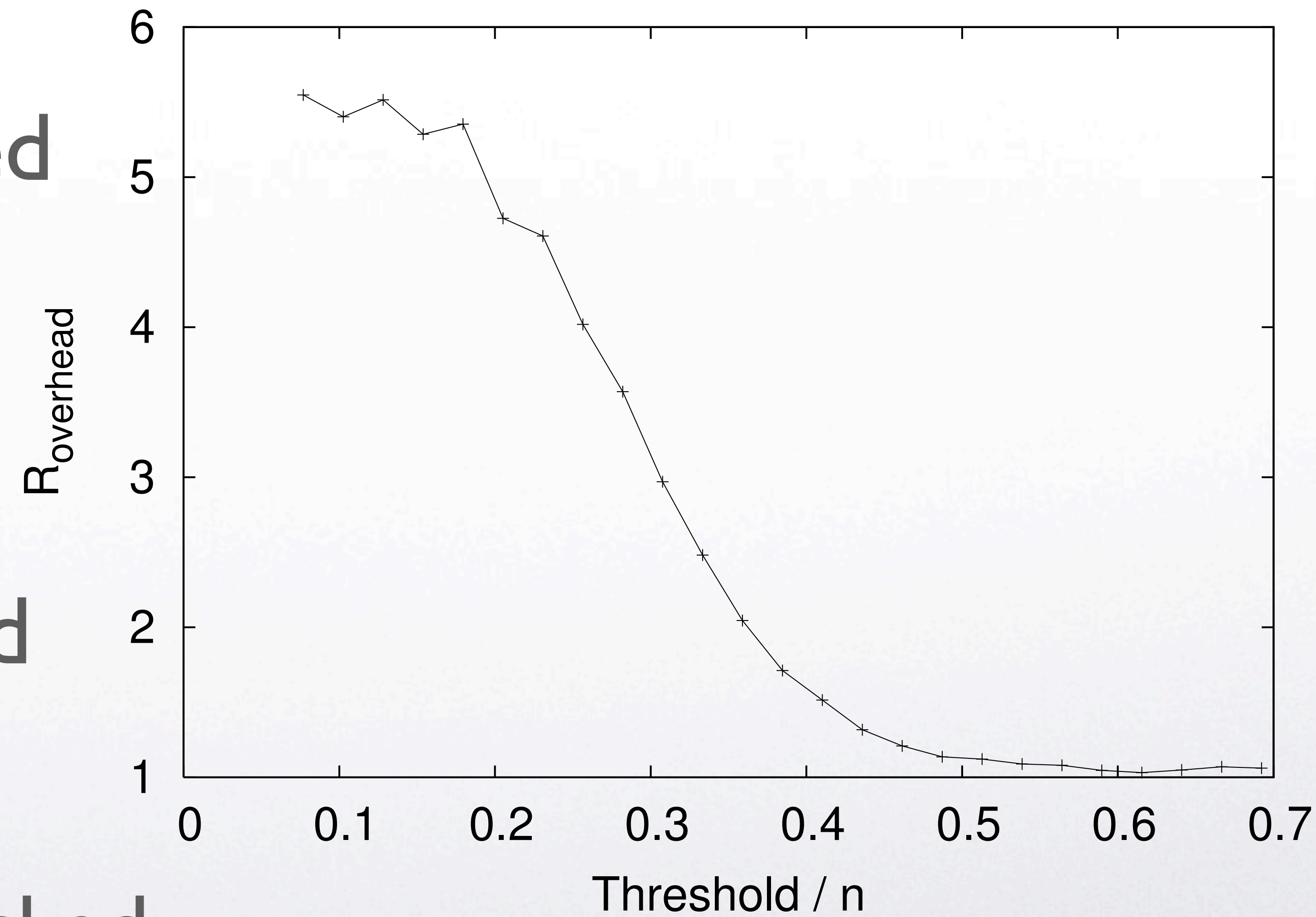
$$R_{\text{overhead}} = \frac{\text{Execution time with signature checking}}{\text{Execution time without signature checking}}$$





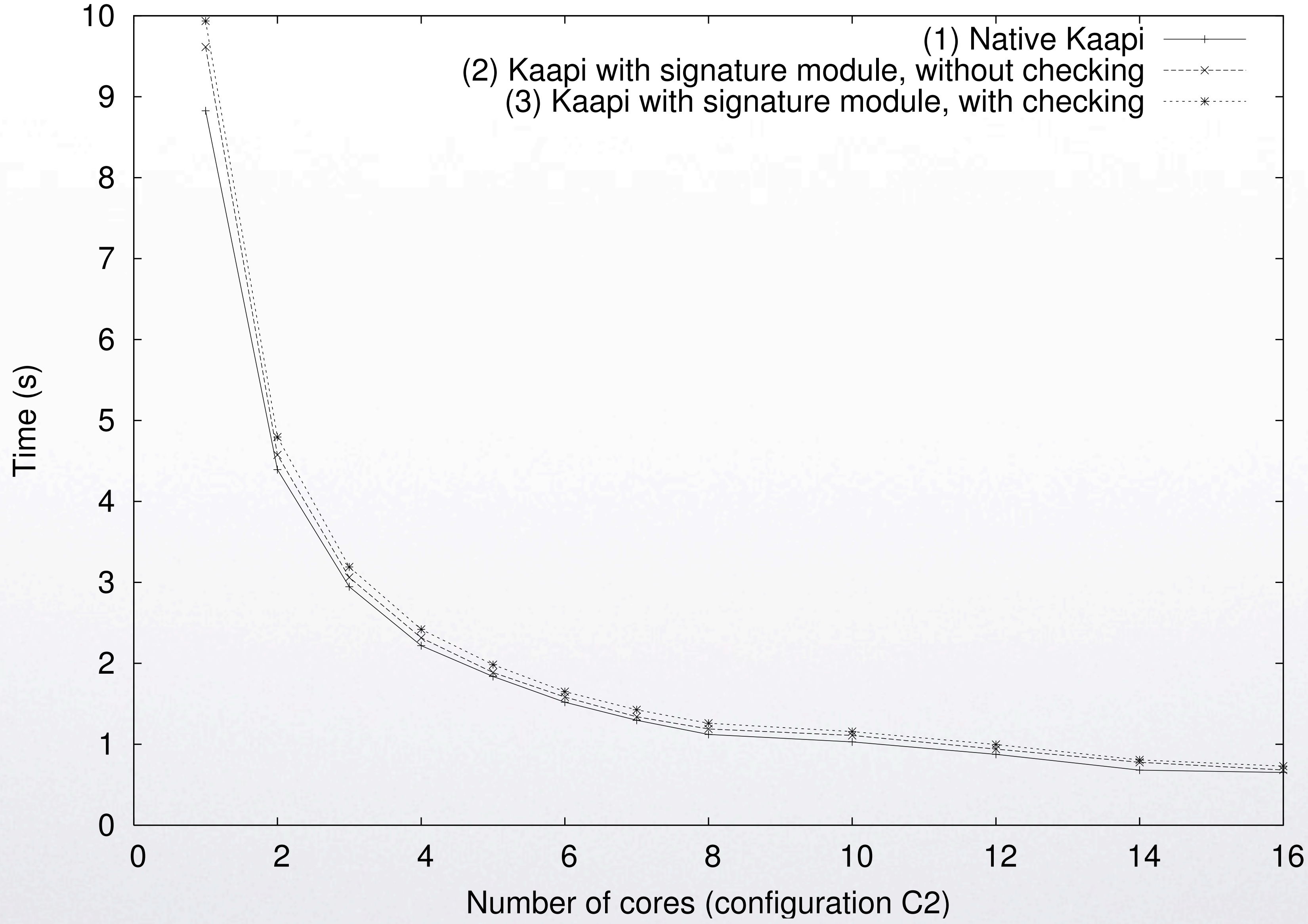
Experiments #1: Fibo(39)

- up to 5.5x overhead
  - huge yet hold in unused parameter area
- for a more realistic threshold (0.5n):
  - relatively low overhead
- scalable approach!
  - Fibo(39)=10^8 tasks checked

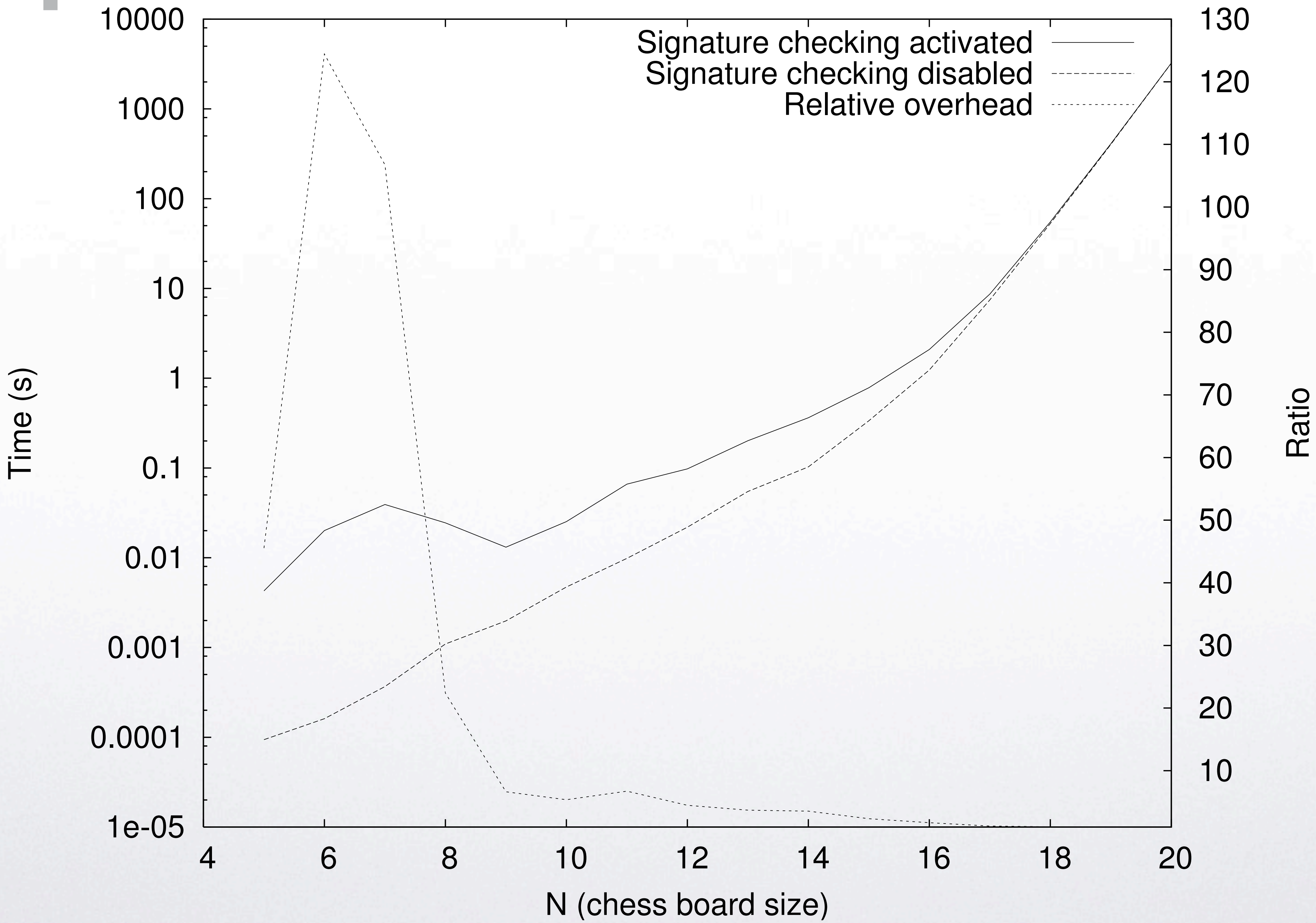


Experiments #1bis: Fibo(42)

- Speedup evaluation (threshold=20)



Experiment #2: N-Queens



Conclusion

- Signature scheme to detect flow faults in distributed computations via macro data-flow analysis
  - offline fingerprint generation by code analysis
  - online distributed & recursive verification
  - fully transparent to the user + working implementation
- Assumes trustable execution agents
  - [Re-trust contribution] investigate way to get ride of this

Last word: conference future

- Mentioned by Yoram
  - C. Collberg wanted to create a more formal conf.
  - ReTrust2008: idea to join our effort on this issue
    - also on board now: Yuan Gu (Cloackware), Paolo Falcarin (P.Torino)
- Current plan: Workshop at ACM Conference on Computer and Communications Security (CCS) 2010
  - Topic: Software protection and Secure computation
    - Paper submission: **April 2010** / Conf: Nov 2010
  - A+ conference, **kindly join the program committee !**