Automatic Distributed Code Generation from Formal Models of Asynchronous Concurrent Processes

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http://convecs.inria.fr

Motivation

- Usage of formal methods
  - specification
  - verification
  - hand-written implementation: time consuming, discrepancies with the specification ?

- **Distributed implementation generation**
  - automatically generates a distributed program

CADP verification toolbox

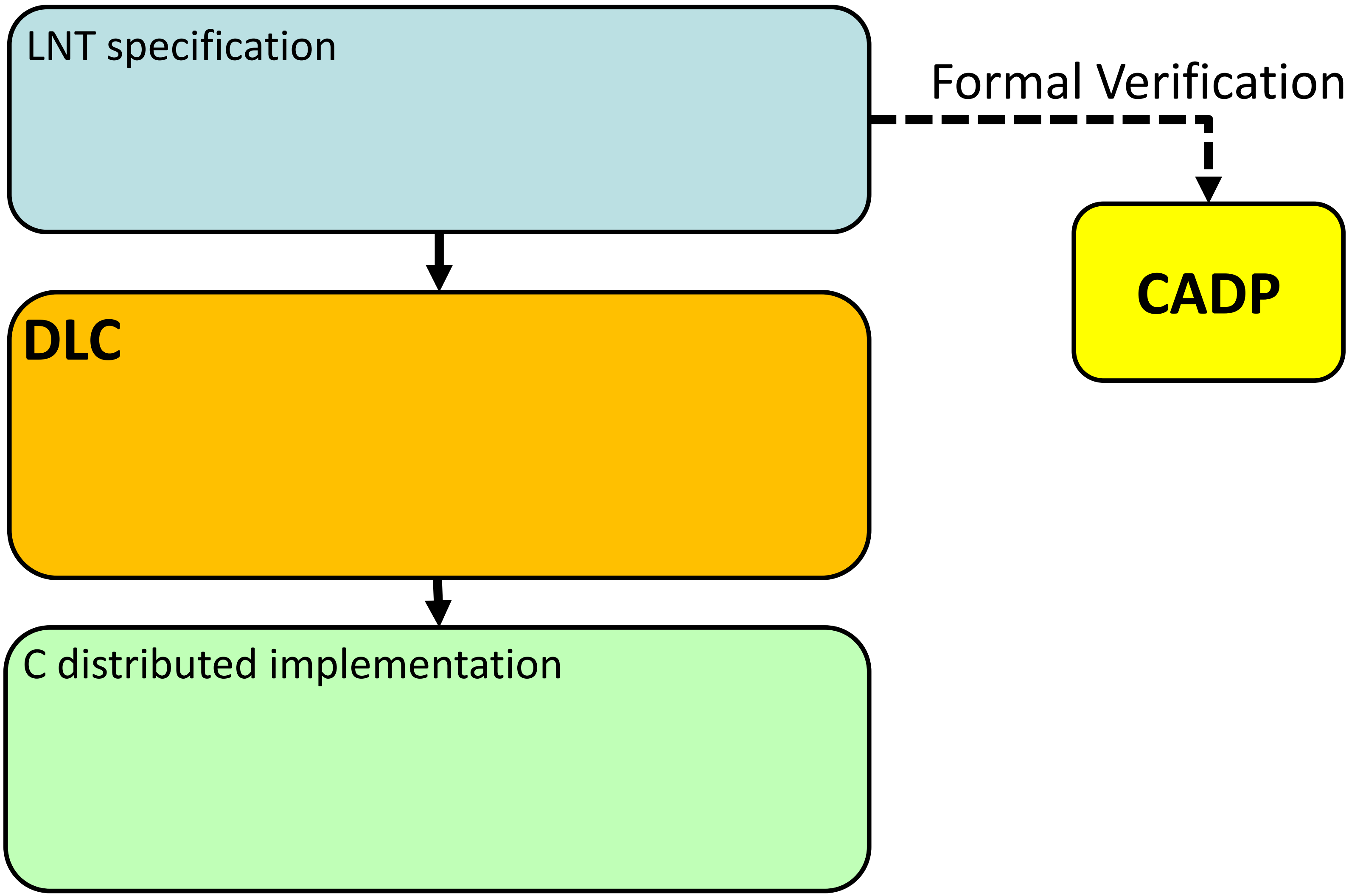
- http://cadp.inria.fr
- **Explicit state techniques:** LTS (*Labeled Transition System*) exploration
- **50+ tools** for LTS manipulation and verification
  - model checking, compositional verification, test generation…
- Main specification language: LNT
  - LNT semantics formally defined in LTS
- EXEC/CAESAR compiler: LNT to sequential C

This talk

- **Aim**: Generate a distributed implementation of a concurrent system from its formal specification (LNT)

- **Contributions**
  - **DLC** (***D**istributed **L**NT **C**ompiler)*
  - from **LNT** to **C and TCP sockets**
  - inter process communication: **multiway rendezvous**
  - interaction with environment: **hook functions**
  - **experimentations**

Distributed LNT Compiler overview



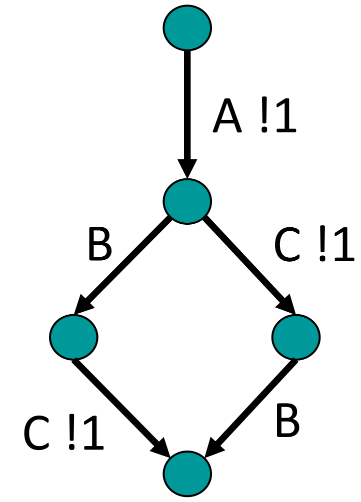
LNT (1)

- A process performs actions on gates
- Process interaction by **multiway rendezvous** on gates
  - Gates are named synchronization points
  - Multiway: **n** processes synchronize (n >= 2)
  - Possibly exchange data by offers

```
process P1 [A,B] is
   A (1); B
end process

process P2 [A,C] is
   var n:nat in
      A (?n); C(n)
   end var
end process
```

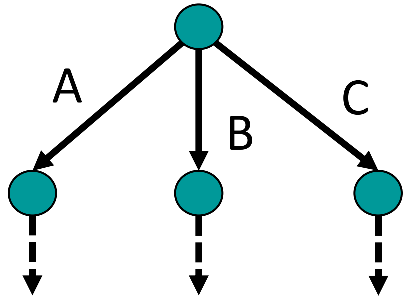
```
(* Parallel composition *)
process MAIN [A,B,C] is
   par A in
      P1 [A,B]
   || P2 [A,C]
   end par
end process
```



LNT (2)

- **Non deterministic choice**: a process is ready on several actions

```
select
   A; …
[] B; …
[] C; …
end select
```



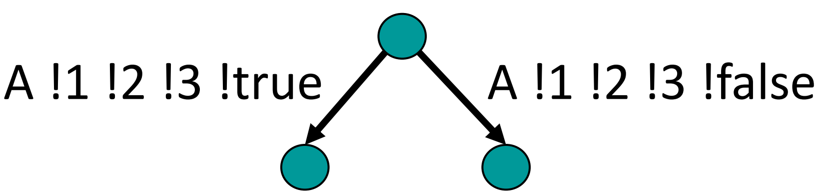
- **General synchronization**: multiple rendezvous per gate, *m*-among-*n*

```
par A, B#2 in
   C -> P1 [A,B,C]
||        P2 [A,B]
|| C -> P3 [A,B,C]
end par
```

  - A: (P1,P2,P3)
  - B: (P1,P2), (P1,P3), (P2,P3)
  - C: (P1, P3)

- **Value-matching data exchange**: send/receive freely combined

```
par A in
   A (1, 2, ?x:nat, ?b1:bool)
|| A (1, ?y:nat, 3, ?b2:bool)
end par
```



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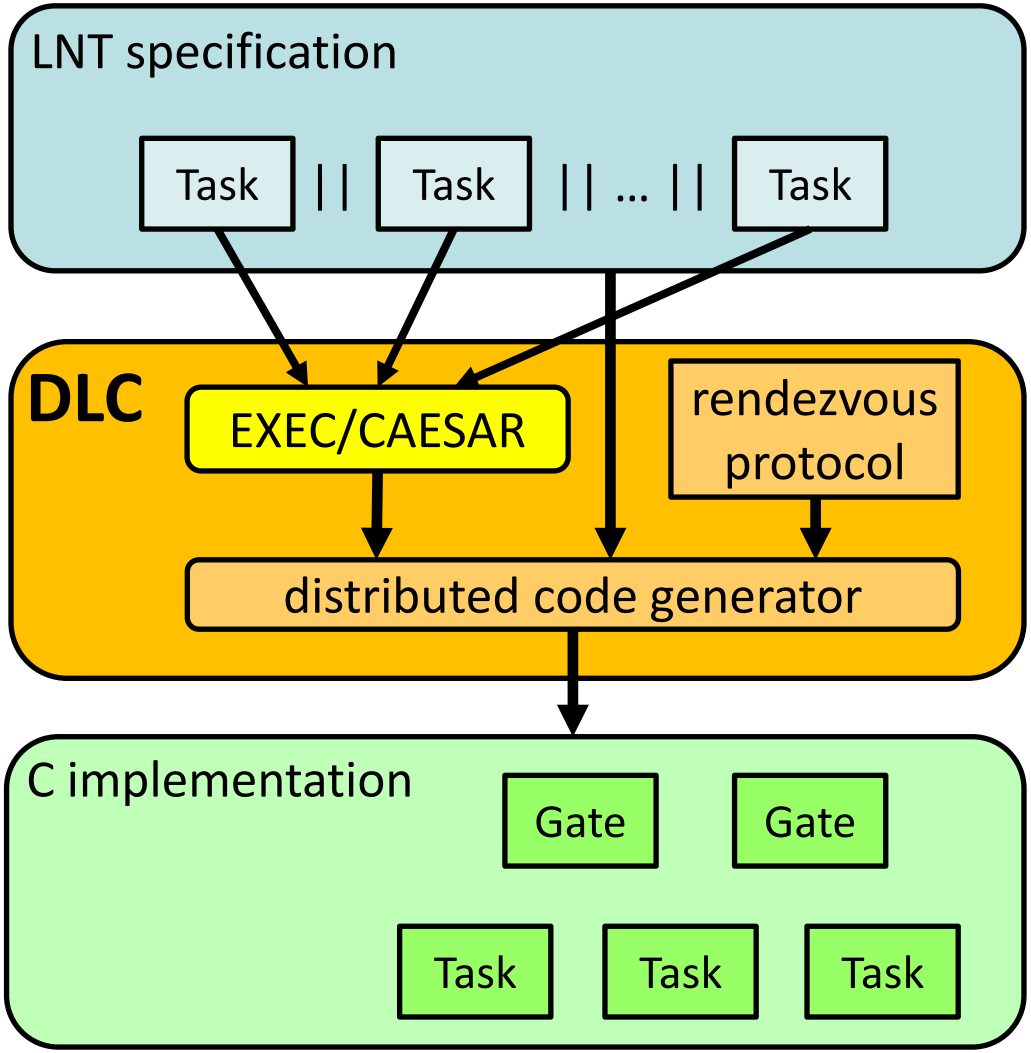


LNT to sequential C

- **EXEC/CAESAR** [Garavel-Viho-Zendri-01]
  - C program that explores an execution path inside the LTS
  - list possible actions from current state
  - still requires code to decide between actions

- DLC **automatically completes** the C program of each task
  - task may synchronize with others for actions
  - adds code to interface with the rendezvous protocol

Multiway rendezvous protocol

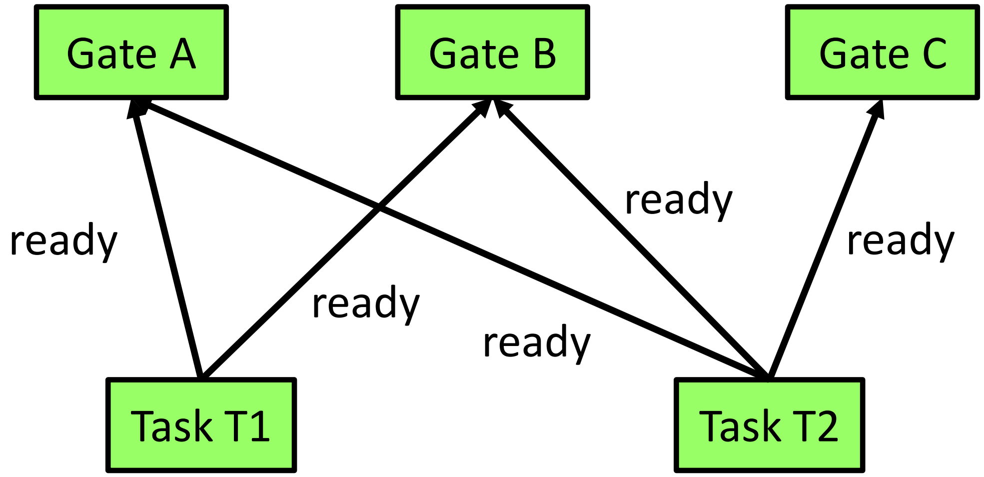
- Role: synchronize task actions
  - a task can be ready on different actions: `select A [] B [] …`
  - all tasks of a rendezvous must commit to the same action
- Requirement: distributed implementation
  - avoid unique central synchronizer (performance bottleneck)
  - protocol relies on asynchronous message passing (TCP: reliable, ordered)
- Solution: based on [Parrow-Sjodin-96]
  - One process per gate, one process per task
  - extended: data exchange, general synchronization

Rendezvous protocol illustration

```
par A, B in
   T1 [A,B]
|| T2 [A,B,C]
end par

process T1 [A,B] is
  select
     A
  [] B
  end select
end process

process T2 [A,B,C] is
  select
     A
  [] B
  [] C; B
  end select
end process
```



- Three phases
  1. Announces: ready
  2. Negotiations: lock (ordered to avoid deadlock)
  3. Results: commit/abort

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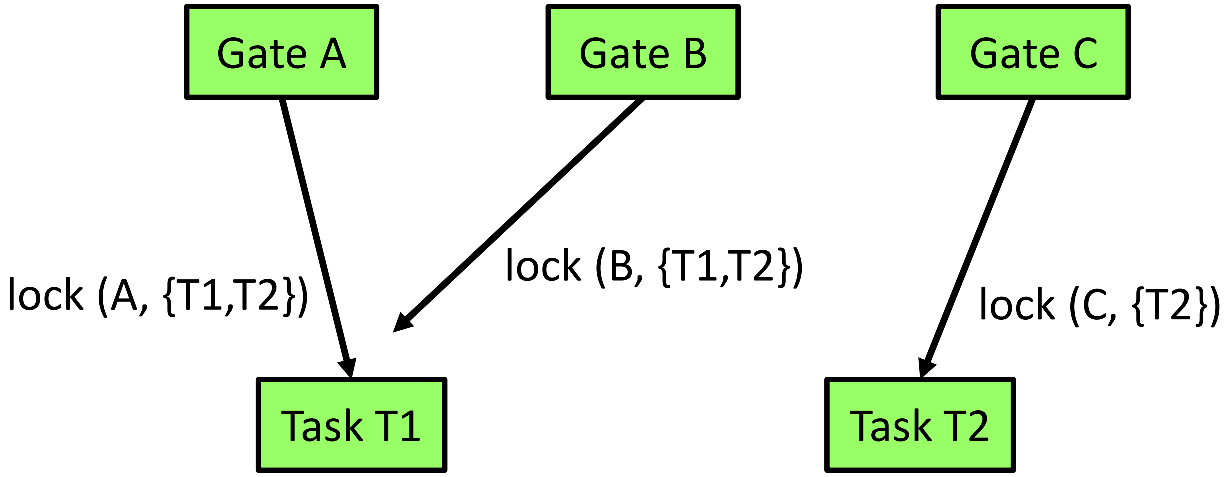

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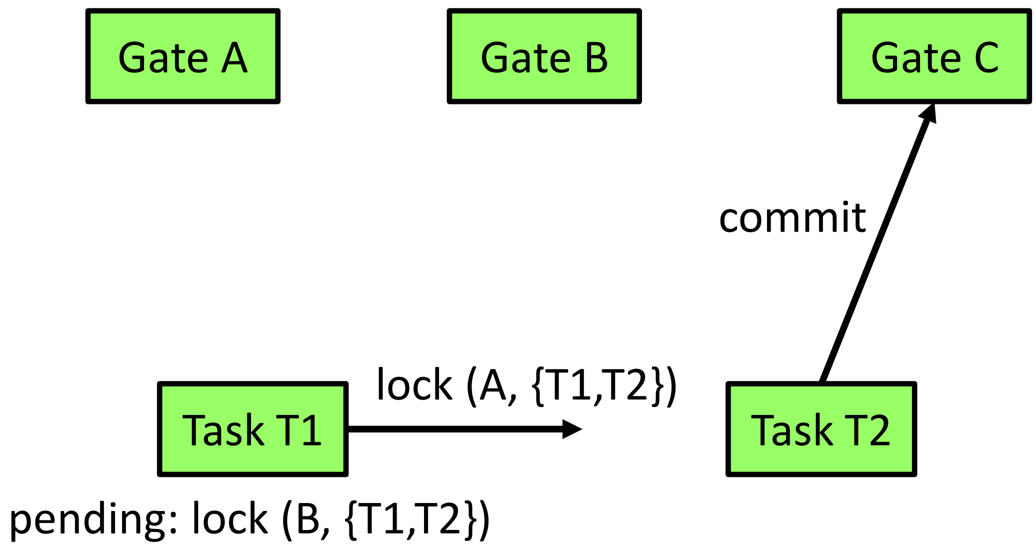

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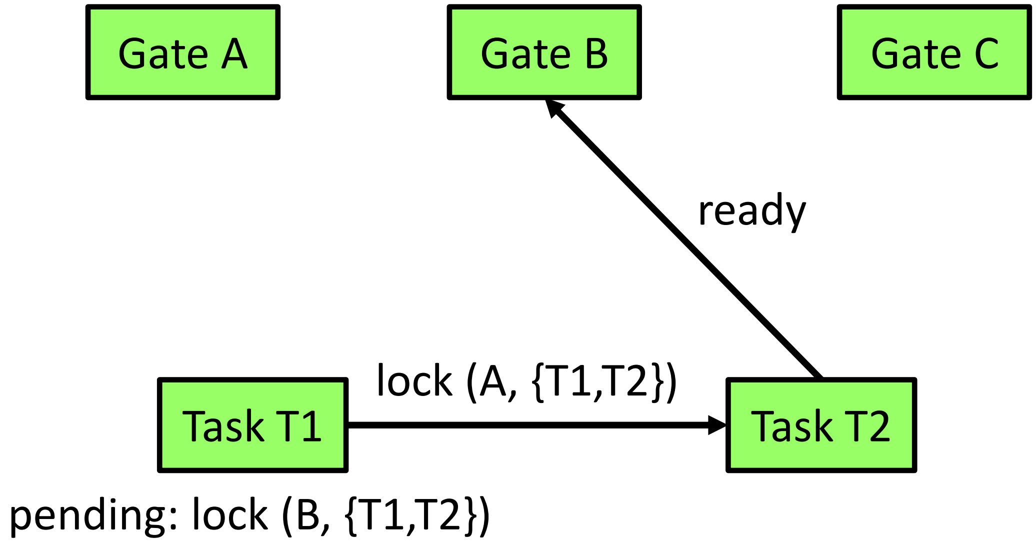

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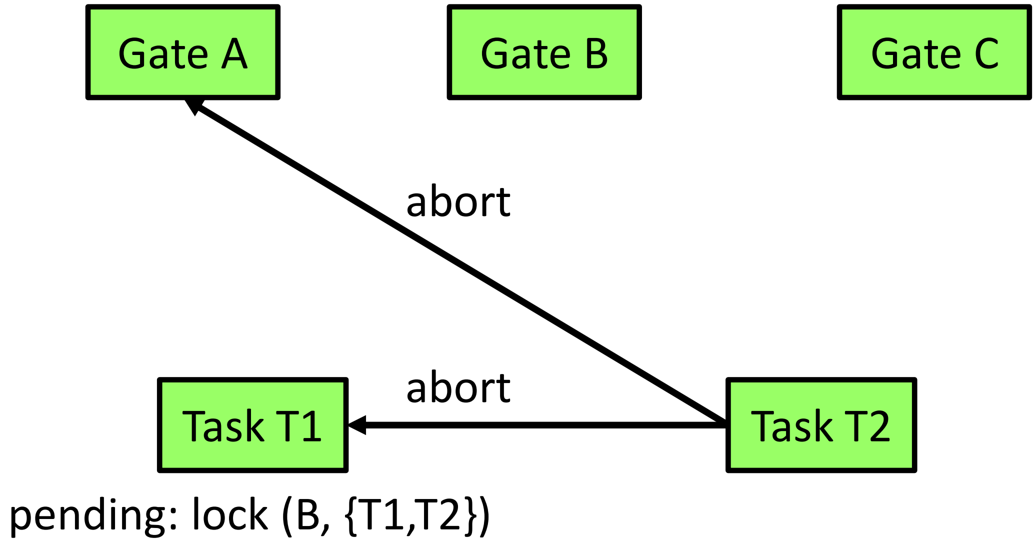

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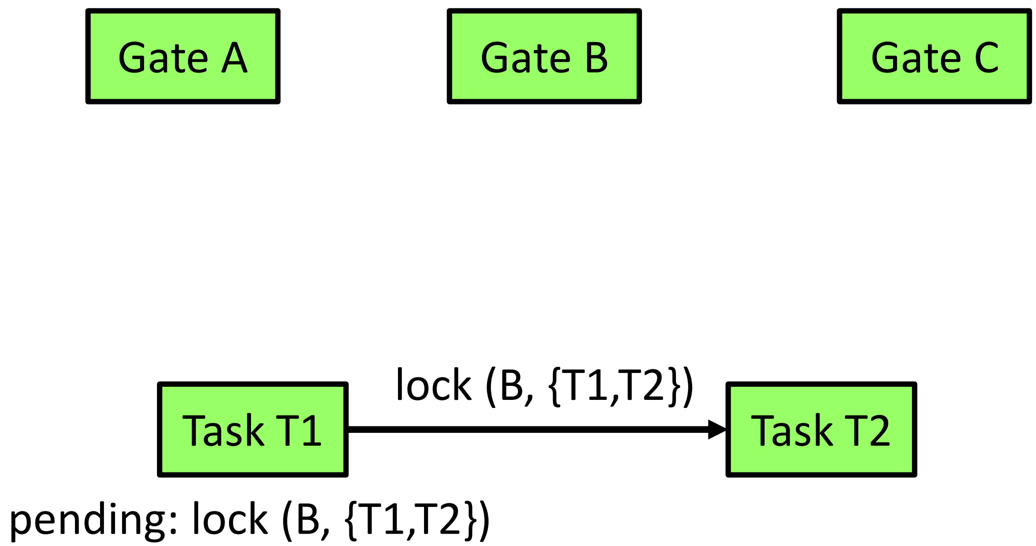

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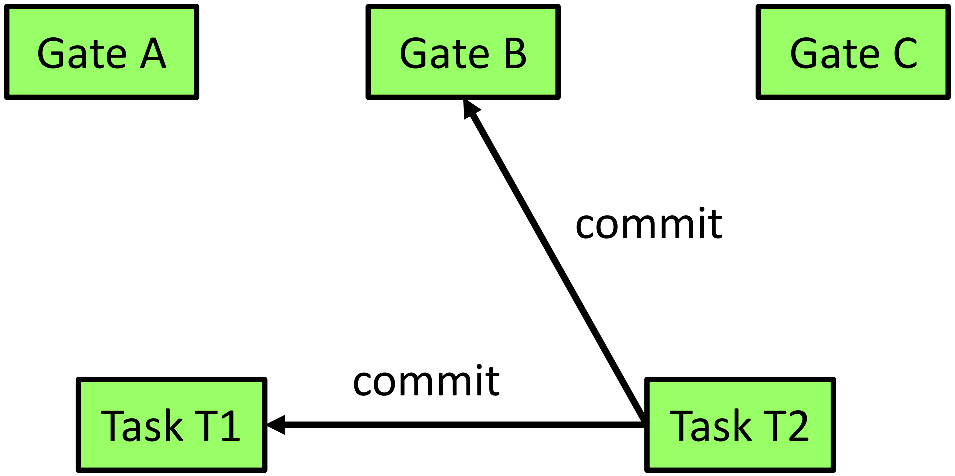

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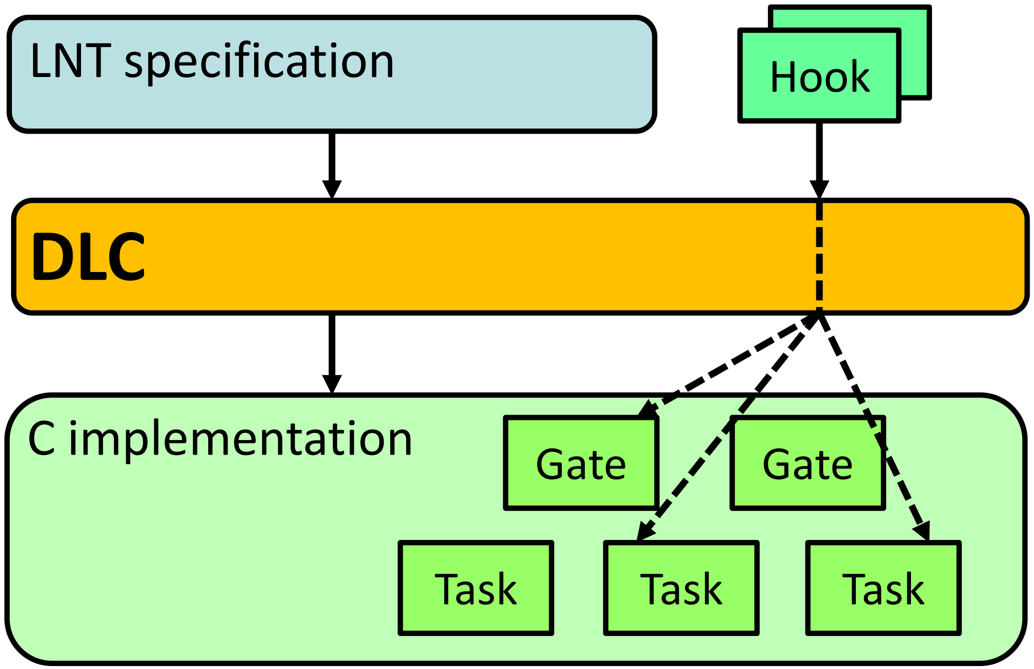
Protocol correctness

- Formal verification with LNT and CADP [Evrard-Lang-13]
  - model checking : absence of protocol livelock/deadlock
  - equivalence checking between implementation & specification
- *"The devil is in the detail"*
  - [Parrow-Sjodin-96] can deadlock with asynchronous messages, fixed version in [Evrard-Lang-13]
  - [Perez-04] can deadlock, fixed version in [Katz-Peled-10]
- DLC version of the protocol
  - protocol logic isolated in a library
  - only glue code that calls protocol is generated for each specification

Interaction with environment: hook functions



- Optional user-defined C function
  - side effects, call external software, …
- Triggered by actions

Three types of hook functions

- **pre-negotiation hook** (one per gate)
  - called before starting a negotiation
  - return bool: authorize negotiation or not
  - role: prevent useless negotiation to hamper others
- **post-negotiation hook** (one per gate)
  - called on negotiation success (tasks are locked, no commit yet)
  - return bool: authorize action or not
  - role: final decision to realize action
- **local hook** (one per task)
  - called by each task that realizes an action
  - role: local side effects at the task level

Exchange data with the environment

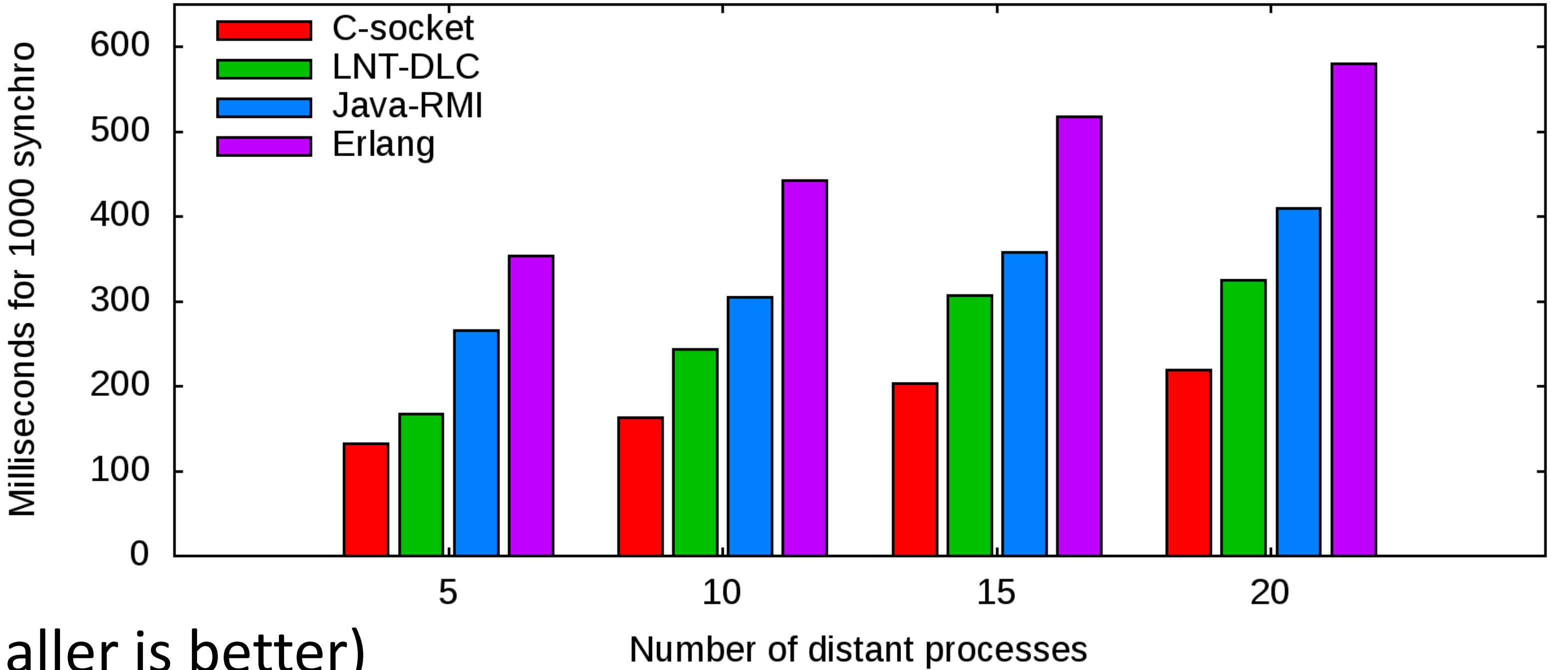
- Hook functions access data offers
- From system to environment
  - offer in send mode: `A (x)`
- From environment to system
  - offer in receive mode: `A (?x)`
  - pre-/post-negotiation hook must define the offer

```
action->offer[0]->value = get_value(); //external function
action->offer[0]->mode  = DLC_MODE_SEND;
```

  - check at runtime: all offers in send mode at the time of negotiation commit

Experimentation: synchro. barrier

- Experimentations on Grid5000
- Compare inter-process interaction perf. with C, Java, …
  - They lack multiway rendezvous (neither built-in nor mature lib)
  - Use distributed synchronization barrier for comparison



(smaller is better)

Experimentation: Raft consensus

- Raft [Ongaro-Ousterhout-14] consensus algorithm (like Paxos)
  - used to build fault tolerant service (replicated state machine)
- Service: storage (read, write)
- LNT Raft cluster
  - use hook functions to implement access from external client
  - 1000 writes replicated on 7 servers: **14000 actions in 5.5 sec**
- Comparison with Consul (in Golang, by Hashicorp)
  - Consul is 10 times faster… batches requests!
  - Raft-level optimization that DLC cannot handle yet

Conclusions

- Generate a distributed implementation from an LNT specification
- Reuse CADP tools for sequential, focus on distribution
- Multiway rendezvous implemented by a verified protocol
- Hook functions enable interaction with environment
- Acceptable performances for rapid prototyping
- new tool **DLC**: automatized compilation, “push button”

Future work

- More case studies of distributed algorithms
  - model in LNT, verify with CADP, compile with DLC
- Improve rendezvous protocol performances (e.g. detect synchronization patterns that require less messages)
- Handle more LNT constructions
  - complex data types (record, list, array…) in action offers
  - guarded actions: `A (?x) where x > 0`

Parrow-Sjodin-96 communication hypothesis

- "*Designing a Multiway Synchronization Protocol*"
- Extract:

2 A Model of Multiway Synchronization

We assume that there are n processes, in the following called *client processes*, communicating over a communication network providing asynchronous point-to-point connections (see Fig. 1). Thus messages will arrive after an unknown and variable delay, and the network never loses messages.

We further assume that there are several multiway synchronization *actions*, denoted a, b

Experimentation: Raft consensus

- Raft consensus algorithm [Ongaro-Ousterhout-14]
  - similar to Paxos, but easier to understand, hence to implement
  - used to build fault tolerant service (replicated state machine)
- Service: storage (read, write)
- LNT Raft cluster
  - use hook functions to implement access from external client
  - 1000 writes replicated on cluster of 7 servers: **5.5 sec**
  - triggers 14000 actions: approx. **0.4ms per action**
- Comparison with Consul (in Golang, by Hashicorp)
  - Consul is 10 times faster… batches requests!
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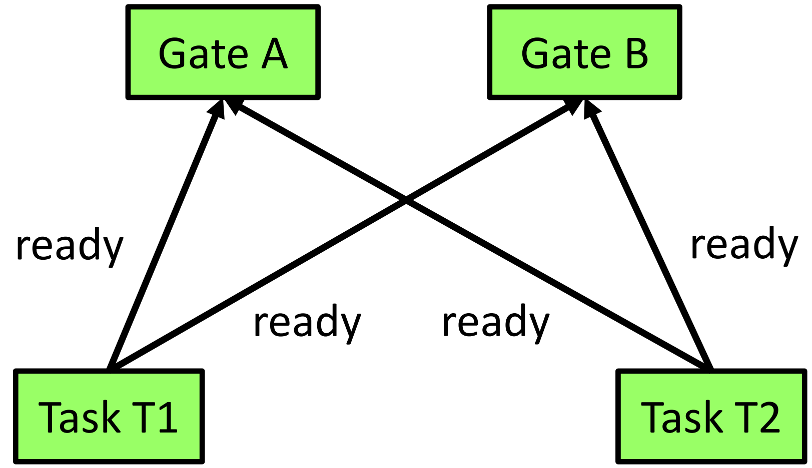

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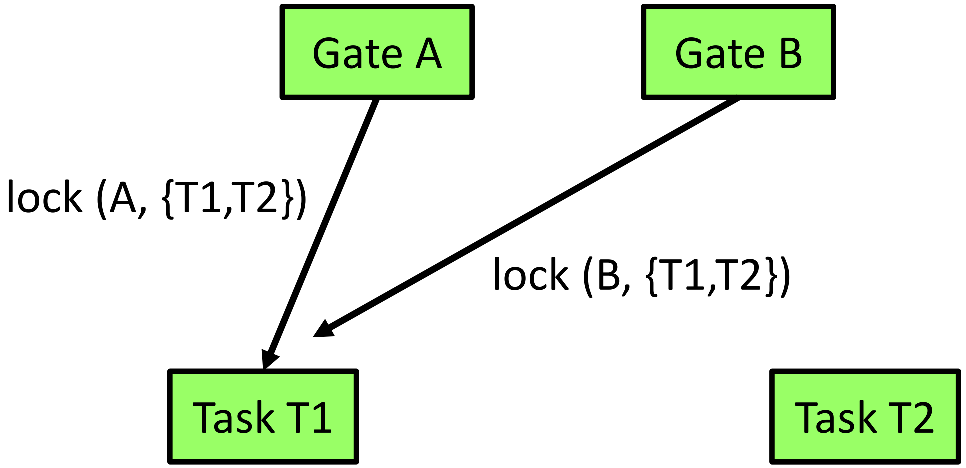

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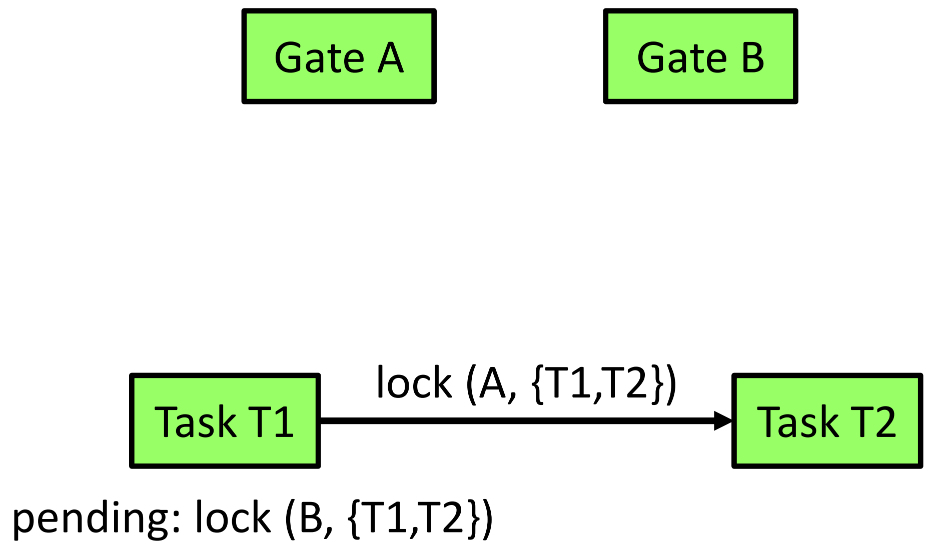

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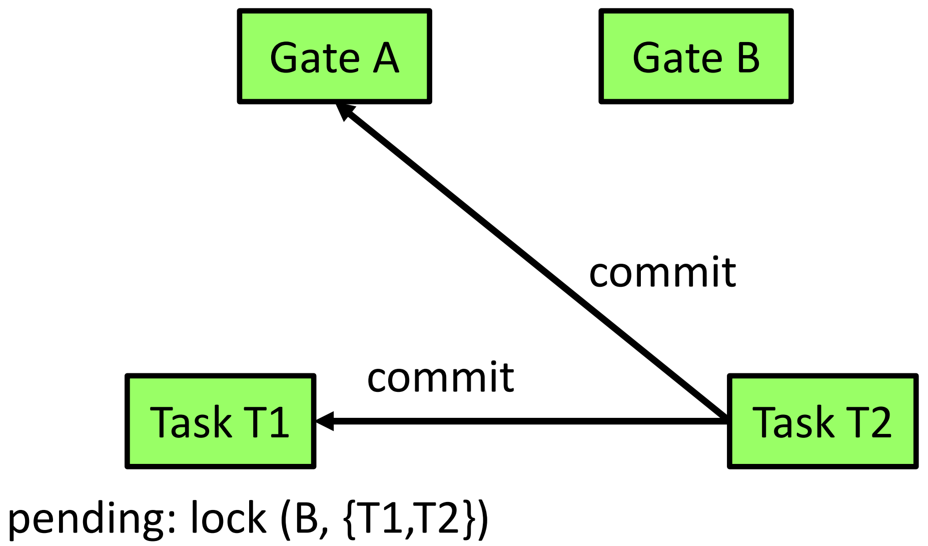

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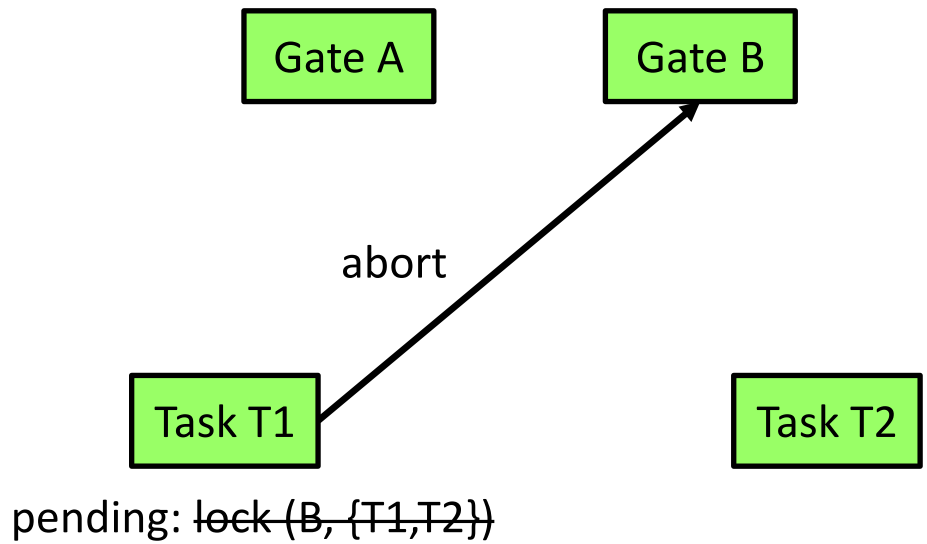

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