Soundness in negotiations.

J. Esparza[1] D. Kuperberg[1,2,3] A. Muscholl[1,2,4] I. Walukiewicz[1,4]

[1]TU Munich, [2]IAS, [3]ENS Lyon, [4]LaBRI,CNRS

Séminaire 68NQRT, IRISA, Rennes
12/01/2017

Introduction

Negotiations [Desel, Esparza '13] CONCUR

- model multiparty distributed cooperation,
- better complexity than alternative models (Petri Nets),
- embeds natural concepts: soundness, race properties,...

This paper [EKMW '16] CONCUR:

- study of different restrictions on the model,
- complexity of deciding soundness, concurrency relationships
- application to workflow analysis for programs

Negotiations

- An atomic negotiation or node involves a set of processes (participants) and has a set of possible outcomes.

Negotiations

- An atomic negotiation or node involves a set of processes (participants) and has a set of possible outcomes.
- If all participants are ready to engage in the node (synchronization), then the node can be fired:
  the processes agree on one of the outcomes (choice) and move on.

Negotiations

- An atomic negotiation or node involves a set of processes (participants) and has a set of possible outcomes.
- If all participants are ready to engage in the node (synchronization), then the node can be fired:
  the processes agree on one of the outcomes (choice) and move on.
- A negotiation $\mathcal{N}$ consists of

Negotiations

- An atomic negotiation or node involves a set of processes (participants) and has a set of possible outcomes.
- If all participants are ready to engage in the node (synchronization), then the node can be fired:
  the processes agree on one of the outcomes (choice) and move on.
- A negotiation $\mathcal{N}$ consists of
  - a set of processes $Proc$,

Negotiations

- An atomic negotiation or node involves a set of processes (participants) and has a set of possible outcomes.
- If all participants are ready to engage in the node (synchronization), then the node can be fired:
  the processes agree on one of the outcomes (choice) and move on.
- A negotiation $\mathcal{N}$ consists of
  - a set of processes $Proc$,
  - a set of outcomes R,

Negotiations

- An atomic negotiation or node involves a set of processes (participants) and has a set of possible outcomes.
- If all participants are ready to engage in the node (synchronization), then the node can be fired:
  the processes agree on one of the outcomes (choice) and move on.
- A negotiation $\mathcal{N}$ consists of
  - a set of processes $Proc$,
  - a set of outcomes R,
  - a set of nodes N
    with two distinguished initial and final nodes,

Negotiations

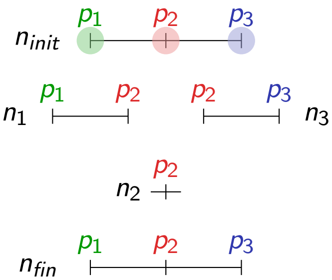
- An atomic negotiation or node involves a set of processes (participants) and has a set of possible outcomes.
- If all participants are ready to engage in the node (synchronization), then the node can be fired:
  the processes agree on one of the outcomes (choice) and move on.
- A negotiation $\mathcal{N}$ consists of
  - a set of processes $Proc$,
  - a set of outcomes R,
  - a set of nodes N
    with two distinguished initial and final nodes,
  - a domain function $dom : N \to \mathcal{P}(Proc)$
    assigning to each node a set of participants,

Negotiations

- An atomic negotiation or node involves a set of processes (participants) and has a set of possible outcomes.
- If all participants are ready to engage in the node (synchronization), then the node can be fired:
  the processes agree on one of the outcomes (choice) and move on.
- A negotiation $\mathcal{N}$ consists of
  - a set of processes $Proc$,
  - a set of outcomes R,
  - a set of nodes N
    with two distinguished initial and final nodes,
  - a domain function $dom : N \to \mathcal{P}(Proc)$
    assigning to each node a set of participants,
  - a transition table $\delta : N \times R \times Proc \to \mathcal{P}(N)$
    $\delta(n, a, p) = \{n', n''\}$ means: if the participants of n choose a, then p is ready to engage in n' or n''.

Run of a negotiation

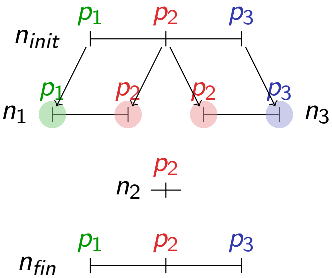
n_{init} initial node, n_{fin} final node.
Here: 3 processes p_1, p_2, p_3 and only one action a.



Run of a negotiation

n_{init} initial node, n_{fin} final node.
Here: 3 processes p_1, p_2, p_3 and only one action a.

$$\delta(n_{init}, a, p_2) = \{n_1, n_3\}$$

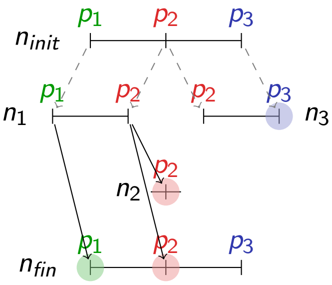


Run of a negotiation

n_{init} initial node, n_{fin} final node.
Here: 3 processes p_1, p_2, p_3 and only one action a.

$$\delta(n_{init}, a, p_2) = \{n_1, n_3\}$$

$$\delta(n_1, a, p_2) = \{n_2, n_{fin}\}$$



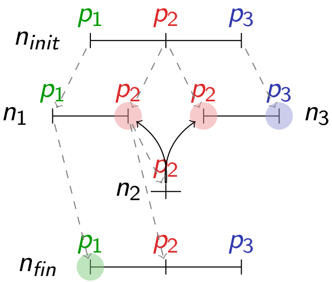
Run of a negotiation

n_{init} initial node, n_{fin} final node.
Here: 3 processes p_1, p_2, p_3 and only one action a.

$$\delta(n_{init}, a, p_2) = \{n_1, n_3\}$$

$$\delta(n_1, a, p_2) = \{n_2, n_{fin}\}$$

$$\delta(n_2, a, p_2) = \{n_1, n_3\}$$



Run of a negotiation

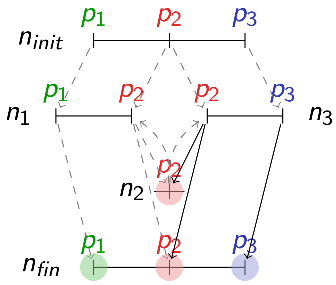
n_{init} initial node, n_{fin} final node.
Here: 3 processes p_1, p_2, p_3 and only one action a.

$$\delta(n_{init}, a, p_2) = \{n_1, n_3\}$$

$$\delta(n_1, a, p_2) = \{n_2, n_{fin}\}$$

$$\delta(n_2, a, p_2) = \{n_1, n_3\}$$

$$\delta(n_3, a, p_2) = \{n_2, n_{fin}\}$$



Run of a negotiation

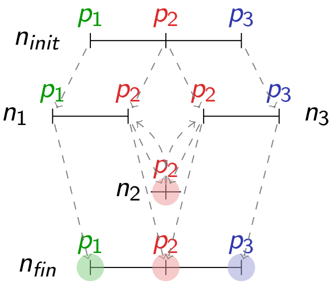
n_{init} initial node, n_{fin} final node.
Here: 3 processes p_1, p_2, p_3 and only one action a.

$$\delta(n_{init}, a, p_2) = \{n_1, n_3\}$$

$$\delta(n_1, a, p_2) = \{n_2, n_{fin}\}$$

$$\delta(n_2, a, p_2) = \{n_1, n_3\}$$

$$\delta(n_3, a, p_2) = \{n_2, n_{fin}\}$$



p_2 is non-deterministic, while p_1 and p_3 are deterministic.

Deterministic and weakly non-deterministic negotiations

- **Deterministic negotiations**: All processes are deterministic.

Deterministic and weakly non-deterministic negotiations

- **Deterministic negotiations**: All processes are deterministic.
- **Weakly non-deterministic negotiations**: Each node involves at least one deterministic process.
- **Acyclic**: No cycle in the transition graph between nodes.

Deterministic and weakly non-deterministic negotiations

- **Deterministic negotiations**: All processes are deterministic.
- **Weakly non-deterministic negotiations**: Each node involves at least one deterministic process.
- **Acyclic**: No cycle in the transition graph between nodes.

Intuition for weakly non-deterministic negotiations:

The negotiation is guided by the deterministic processes. Non-deterministic processes are “told” where to go by the deterministic ones.

Deterministic and weakly non-deterministic negotiations

- **Deterministic negotiations**: All processes are deterministic.
- **Weakly non-deterministic negotiations**: Each node involves at least one deterministic process.
- **Acyclic**: No cycle in the transition graph between nodes.

Intuition for weakly non-deterministic negotiations:

The negotiation is guided by the deterministic processes. Non-deterministic processes are “told” where to go by the deterministic ones.

Research program: investigate the complexity of analysis problems for deterministic and weakly non-deterministic negotiations.

The Soundness problem

Soundness property

Soundness:
Every partial run can be completed into an accepting run.
Non-blocking property, witnessing good design.

Example: Previous negotiation is sound.

Soundness property

Soundness:
Every partial run can be completed into an accepting run.
Non-blocking property, witnessing good design.

Example: Previous negotiation is sound.

Aim: Understand the fine-grained complexity of the following problem, depending on restrictions on $\mathcal{N}$:
INPUT: A negotiation $\mathcal{N} = (N, Proc, R, \delta)$.
OUTPUT: Is $\mathcal{N}$ sound ?

Subclasses of negotiations

Soundness problem PSPACE-complete in general [DE '13].

Complexity of the soundness problem for *classes of negotiations*?

Theorem (DE '14)

Deciding soundness is in PTIME for deterministic negotiations.

This paper [EKMW '16]: explores the room between the two.

Results on the complexity of the soundness problem

Theorem (EKMW '16)

Deciding soundness is in PTIME for acyclic weakly non-deterministic negotiations.

Main tool used in the proof: the Omitting Theorem.

Theorem (EKMW '16)

It can be decided in PTIME if for a given deterministic, acyclic, and sound negotiation $\mathcal{N}$ and two sets $P \subseteq N \times R$ and $B \subseteq N$, there is a successful run of $\mathcal{N}$ containing P and omitting B.

General interest: characterize the important parts of a negotiation.

Soundness problem for bigger classes

What happens if we drop restrictions in the previous results ?
Dropping weak non-determinism:

Theorem (EKMW '16)

The soundness problem for acyclic negotiations is coNP-complete.

Soundness problem for bigger classes

What happens if we drop restrictions in the previous results ?
Dropping weak non-determinism:

Theorem (EKMW '16)

The soundness problem for acyclic negotiations is coNP-complete.

Dropping acyclicity for a milder constraint:

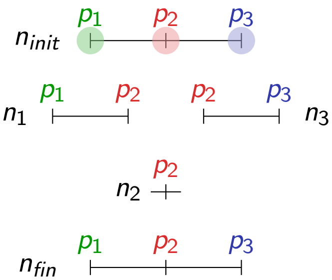
Theorem (EKMW '16)

*The soundness problem for **det-acyclic** weakly non-deterministic negotiations is coNP-complete.*

Det-acyclicity: deterministic processes are acyclic.
Enough here to prevent cycles in actual runs.

Det-acyclicity example

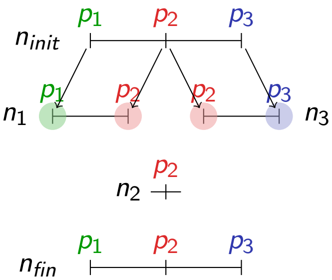
Det-acyclicity + Weak ND $\implies$ no cycles in runs,
Here not weakly ND.



Det-acyclicity example

Det-acyclicity + Weak ND $\implies$ no cycles in runs,
Here not weakly ND.

$$\delta(n_{init}, a, p_2) = \{n_1, n_3\}$$

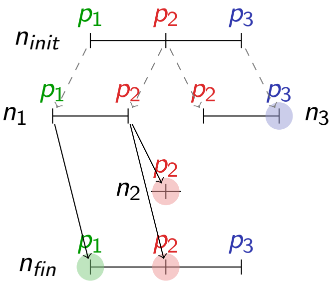


Det-acyclicity example

Det-acyclicity + Weak ND $\implies$ no cycles in runs,
Here not weakly ND.

$$\delta(n_{init}, a, p_2) = \{n_1, n_3\}$$

$$\delta(n_1, a, p_2) = \{n_2, n_{fin}\}$$



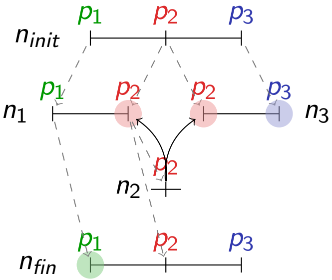
Det-acyclicity example

Det-acyclicity + Weak ND $\implies$ no cycles in runs,
Here not weakly ND.

$$\delta(n_{init}, a, p_2) = \{n_1, n_3\}$$

$$\delta(n_1, a, p_2) = \{n_2, n_{fin}\}$$

$$\delta(n_2, a, p_2) = \{n_1, n_3\}$$



Det-acyclicity example

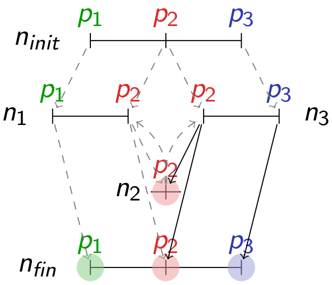
Det-acyclicity + Weak ND $\Longrightarrow$ no cycles in runs,
Here not weakly ND.

$\delta(n_{init}, a, p_2) = \{n_1, n_3\}$

$\delta(n_1, a, p_2) = \{n_2, n_{fin}\}$

$\delta(n_2, a, p_2) = \{n_1, n_3\}$

$\delta(n_3, a, p_2) = \{n_2, n_{fin}\}$



Det-acyclicity example

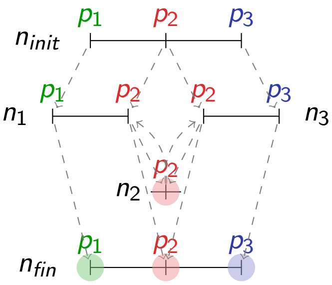
Det-acyclicity + Weak ND $\implies$ no cycles in runs,
Here not weakly ND.

$$\delta(n_{init}, a, p_2) = \{n_1, n_3\}$$

$$\delta(n_1, a, p_2) = \{n_2, n_{fin}\}$$

$$\delta(n_2, a, p_2) = \{n_1, n_3\}$$

$$\delta(n_3, a, p_2) = \{n_2, n_{fin}\}$$



Applications of sound negotations

Races

Race Problem:
GIVEN: a negotiation $\mathcal{N}$, and two nodes n, m of $\mathcal{N}$.
DECIDE: can n and m be concurrently enabled ?

Races

Race Problem:
GIVEN: a negotiation $\mathcal{N}$, and two nodes n, m of $\mathcal{N}$.
DECIDE: can n and m be concurrently enabled ?

- standard question for concurrent systems
- inherently concurrent property, hard to work with linearizations

Complexity of the race problem

The race problem is PSPACE-complete in the general case and NP-complete for acyclic negotiations.

Determinism alone does not help:

Theorem (EKMW '16)

The race problem stays PSPACE-complete and NP-complete for deterministic and acyclic deterministic negotiations.

Complexity of the race problem

The race problem is PSPACE-complete in the general case and NP-complete for acyclic negotiations.

Determinism alone does not help:

Theorem (EKMW '16)

The race problem stays PSPACE-complete and NP-complete for deterministic and acyclic deterministic negotiations.

But determinism **and** soundness **together** help:

Theorem (EKMW '16)

The race problem is

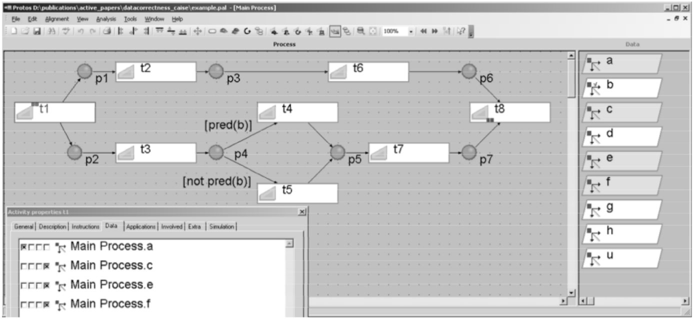
- *in PTIME for sound deterministic negotiations.*
- *NLOGSPACE-complete for sound deterministic acyclic negotiations,*

Workflow Analysis

Application of negotiations: analyze the workflow of programs.

Data-flows: Petri-net-based modeling notation, widely used (Protos) [van der Aalst et al, '09].

Model the behaviour of programs or protocols acting on global variables via operations: *alloc*(x), *read*(x), *write*(x), *dealloc*(x).



Negotiations for data-flow analysis

Sound acyclic deterministic negotiations with variables
$\rightsquigarrow$ formalize data-flow problems from [van der Aalst et al, '09]:

- **Well-defined behaviour**: no concurrent operations on the same variable,
- **No redundancy**: allocated variables are used,
- **Clean memory**: allocated variables are deallocated.

Negotiations for data-flow analysis

Sound acyclic deterministic negotiations with variables
$\rightsquigarrow$ formalize data-flow problems from [van der Aalst et al, '09]:

- **Well-defined behaviour**: no concurrent operations on the same variable,
- **No redundancy**: allocated variables are used,
- **Clean memory**: allocated variables are deallocated.

Theorem (EKMW '16)

All these properties can be checked in PTIME on data-flows.

Proof using the Omitting Theorem.

Exponential improvement on [van der Aalst et al, '09].

Trace Property testing

Data-flow result: Embeds typical specifications into a class of trace properties easy to decide (PTIME).

All these properties can be described by fixed-size automata with simple structure.

Can we generalize this ?

Trace Property testing

Data-flow result: Embeds typical specifications into a class of trace properties easy to decide (PTIME).

All these properties can be described by fixed-size automata with simple structure.

Can we generalize this ?

Theorem (Unpublished)

There is a property P specified by a 6-state automaton such that checking P for a sound acyclic deterministic negotiation is **NP-complete***.*

We get a fine-grained description of the difficulty of trace property checking.

Conclusion

- **The negotiation model provides new insights** on what makes communicating finite-state processes hard to analyze.
- **Soundness is a key property** that can decrease the complexity of checking other properties.
- **Detailed picture** of complexities of property checking.
- **Applications** to the static analysis of workflow processes.

Conclusion

- **The negotiation model provides new insights** on what makes communicating finite-state processes hard to analyze.
- **Soundness is a key property** that can decrease the complexity of checking other properties.
- **Detailed picture** of complexities of property checking.
- **Applications** to the static analysis of workflow processes.

Open problem
Soundness for Weakly non-deterministic negotiations:
PSPACE-complete ? coNP-complete ?.