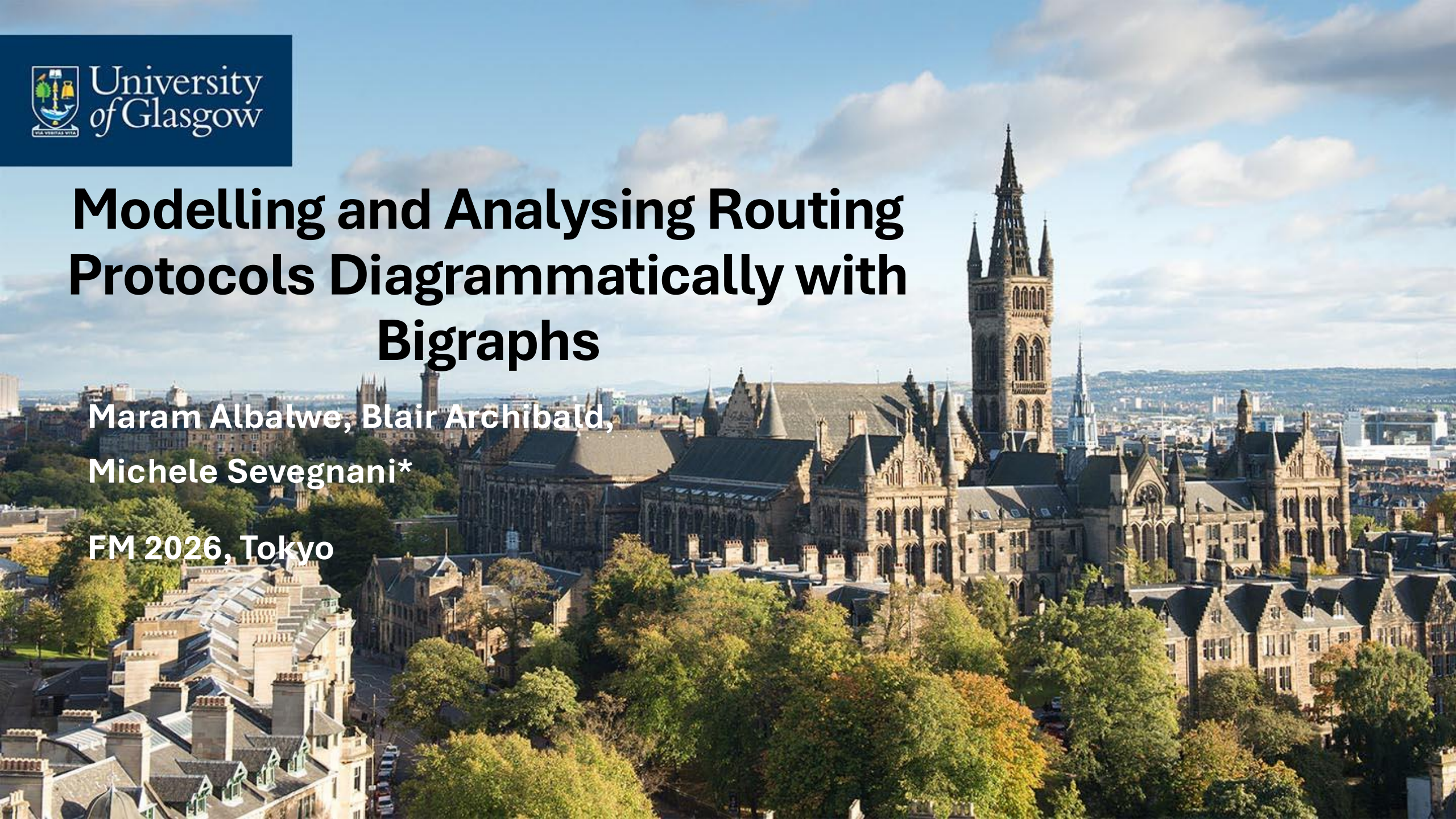

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Modelling and Analysing Routing Protocols Diagrammatically with Bigraphs

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Protocol design practice

Simulation/emulation is standard practice

- Implementation fidelity is a strength
- Coverage is necessarily partial
- Exploring variants has engineering cost

Formal methods offer exhaustive reasoning

- But modelling notations can be hard to adopt
- Usability and scalability remain practical barriers

Question: can we keep rigour while improving modelling usability?

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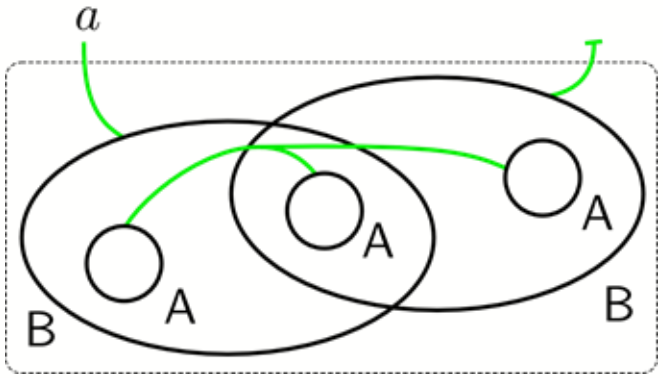
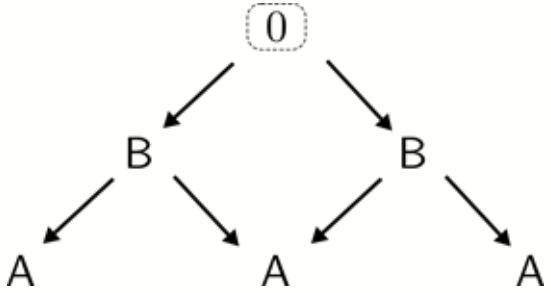
Bigraphs: structure

1. Bigraph: superimposition of a **place graph** and a **link graph**
2. Place graph (**with sharing**): **DAG** - topological space - no distances - containment relation
3. Link graph: **Hypergraph** - relationships between sets of entities (e.g. communication capabilities)



Bigraph



Place graph

Link graph

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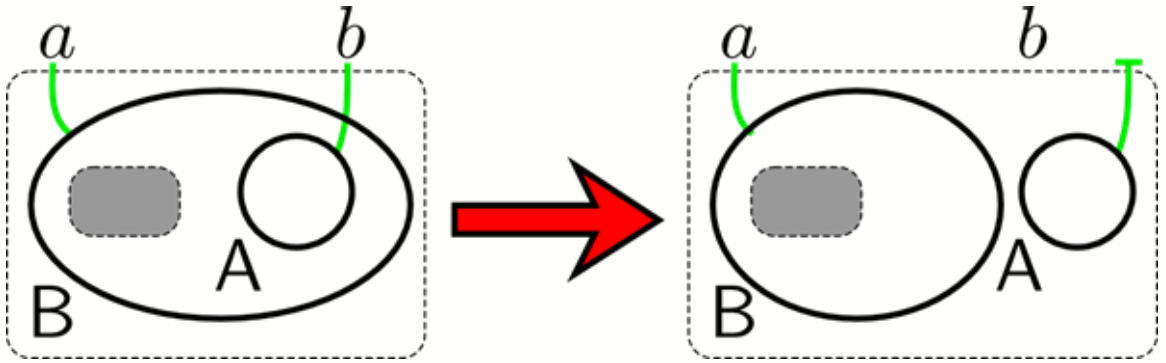
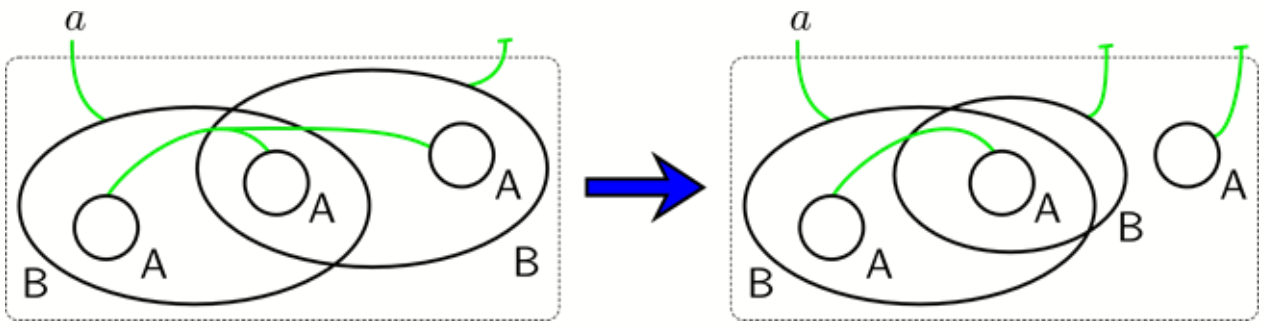
Bigraphs: dynamics

- Specified by a set of reaction rules
  1. Identify occurrences of the lhs in the bigraph
  2. Substitute each occurrence with the rhs (rewriting)
- Global behaviour emerges from all possible rule applications

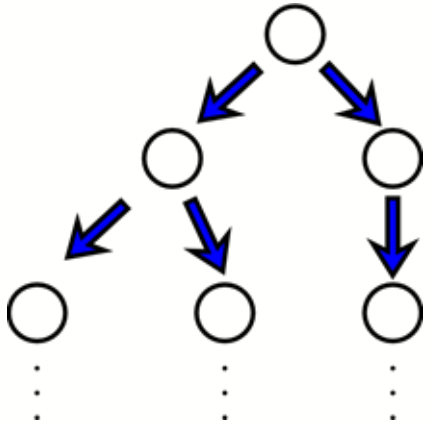


Bigraphical Reactive Systems

- An **initial** bigraph and a **set** of reaction rules
- By performing all the rewriting steps we find all the reachable configurations of the system
- The resulting transition system can be labelled and model checked



Transition



Transition system

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Approach overview

1. Encode network topologies as bigraphs
2. Define behaviour via reaction rules
3. Generate the labelled transition system (for a given topology)
4. Validate model by verifying properties with a model checker
5. Compare our model against a popular simulation-based approach

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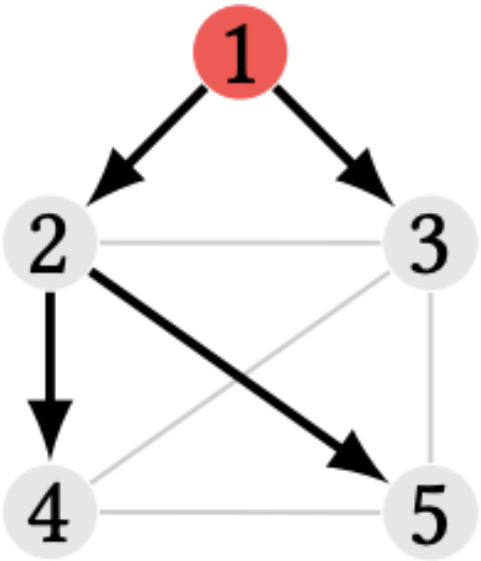
RPL: Routing Protocol for Low-power and Lossy Networks

- RPL builds a DAG that defines an optimal routing path from the root to each reachable node
- There are four control messages

1. DIS (DAG Information Solicitation): requests information about a nearby DAG
2. DIO (DAG Information Object): transmits information, e.g. rank, to other nodes
3. DAO (Destination Advertisement Object): used by nodes joining the DAG to update other nodes with new routing information
4. DAO-ACK (Destination Advertisement Object Acknowledgement): sent by the root to a joining node



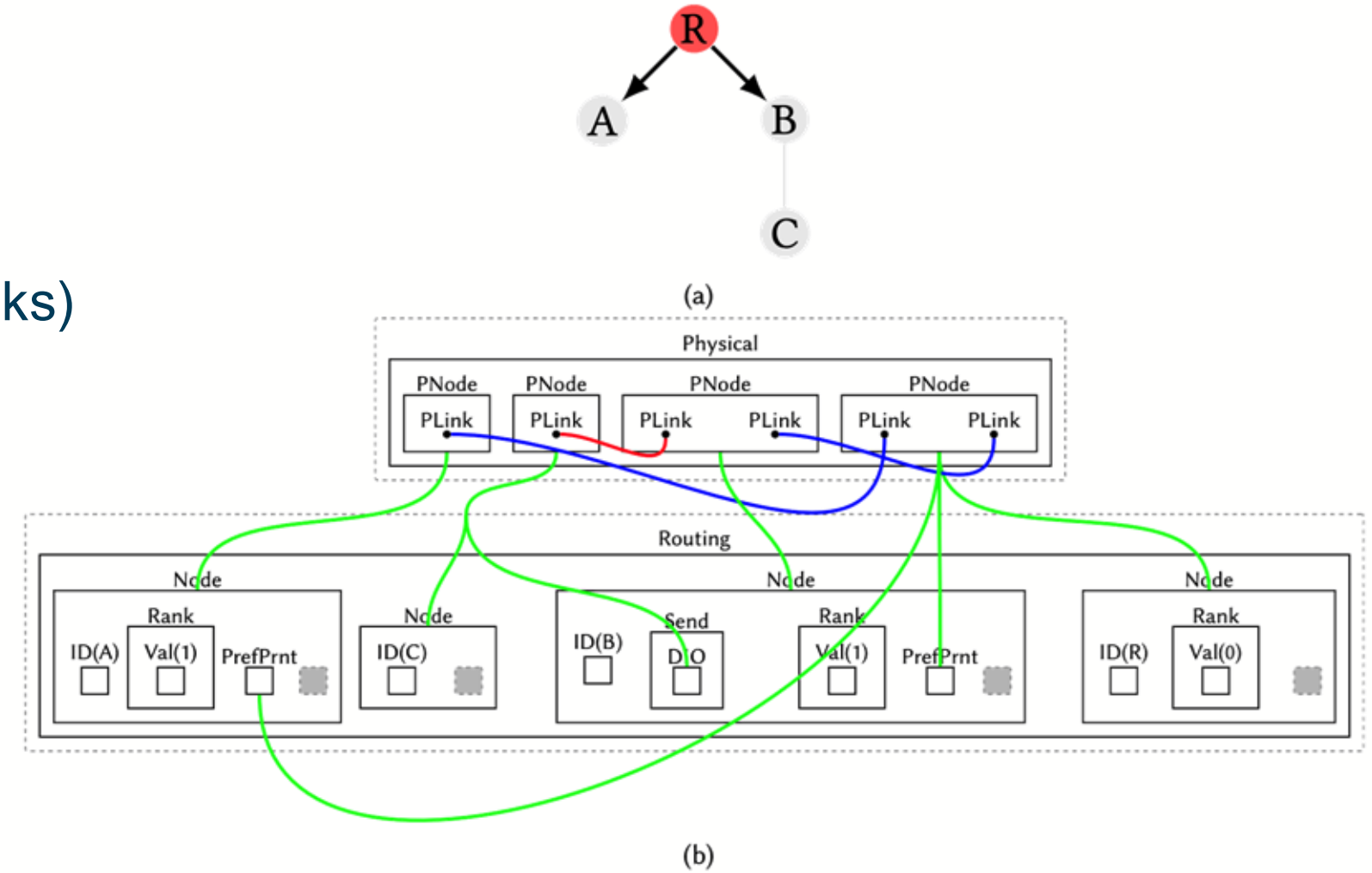
Modelling structure: two perspectives

Physical perspective

- PNode
- PLink (for radio links)

Routing perspective

- Node
- Rank
- Messages
- ….



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Modelling RPL dynamics

- 16 reaction rules encoding the four main steps of the RPL DAG constructions
- Rules can only rely on local context to encode the behaviour of RPL
- Complex operations like rank comparison and multicast are encoded by multiple rules
- We also assign priorities to control the order in which rules are applied

- I will only show two rules

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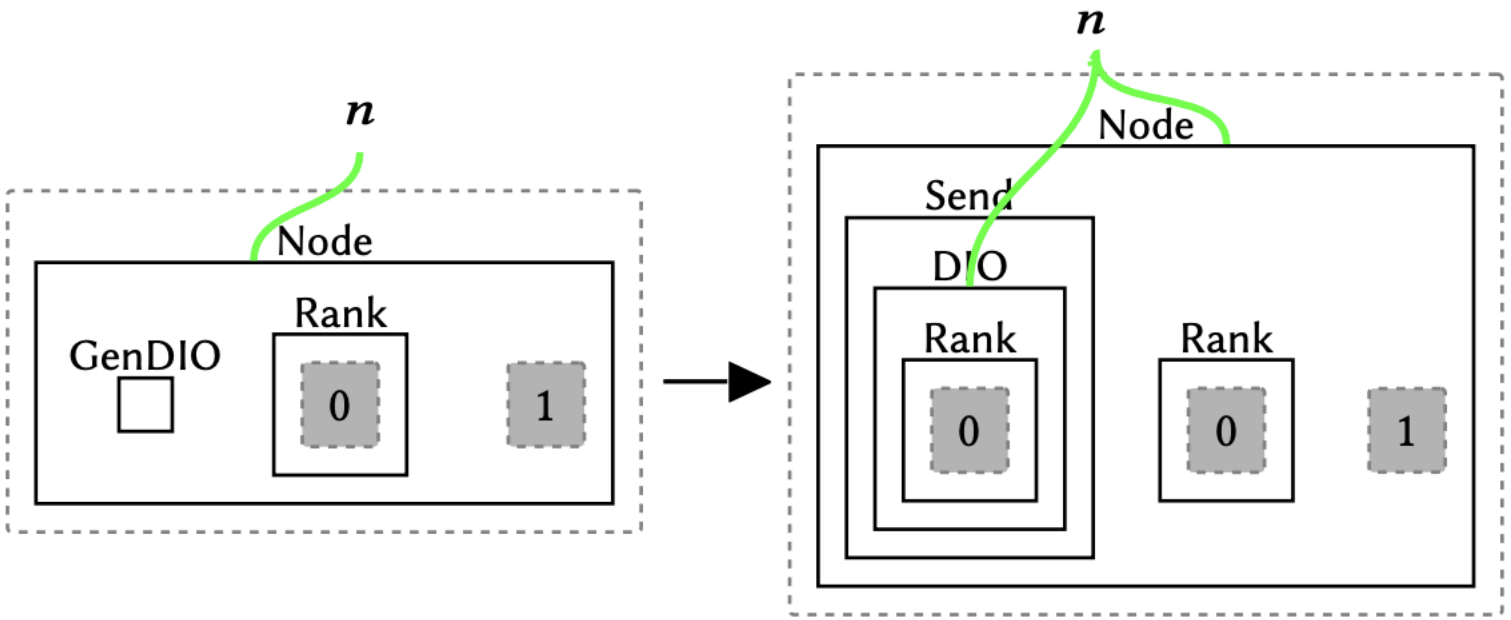
Modelling RPL dynamics: generate DIOs

We use an instantiation map to duplicate the content of Rank in the rhs



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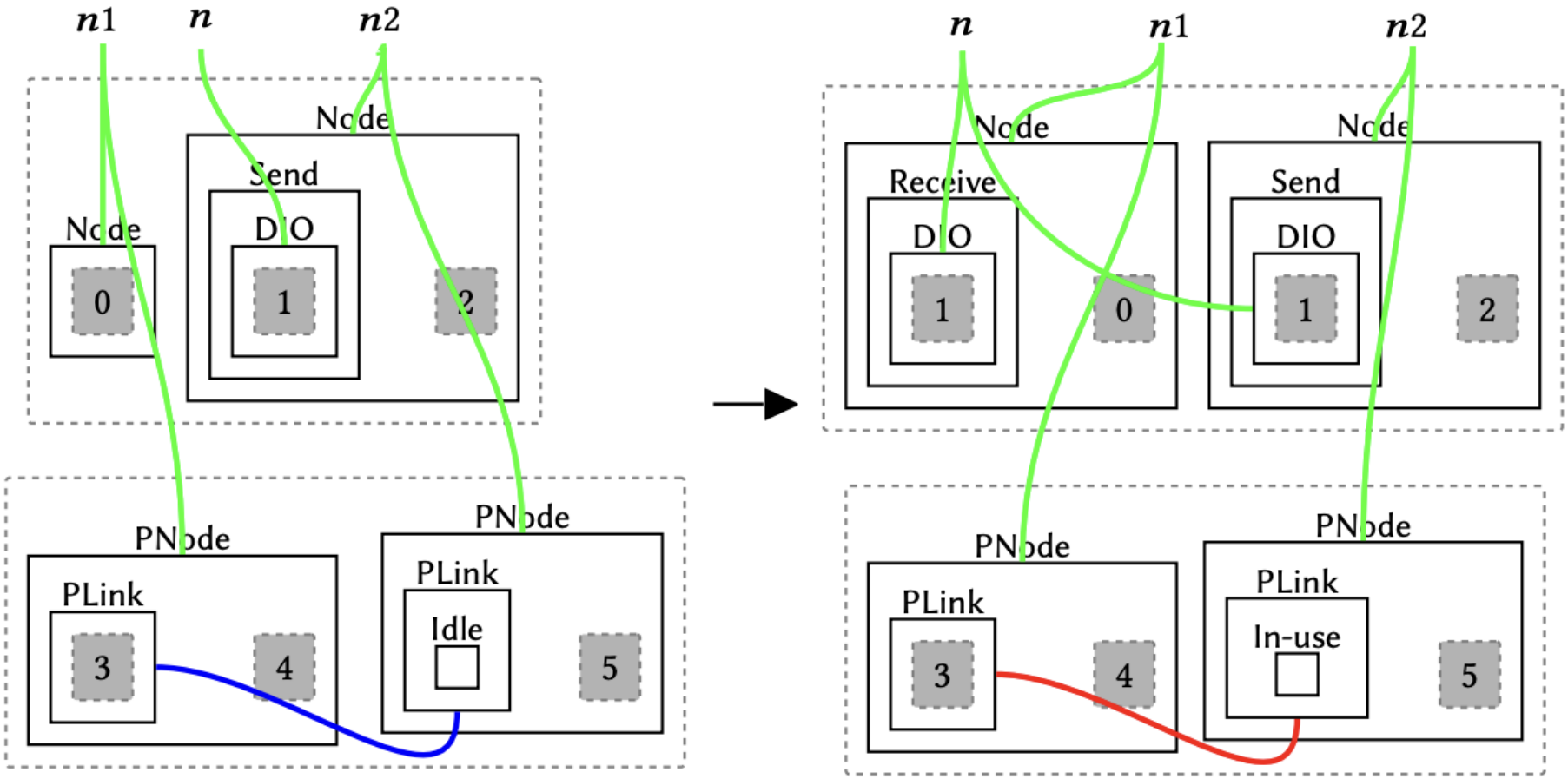
Modelling RPL dynamics: multicast DIOs



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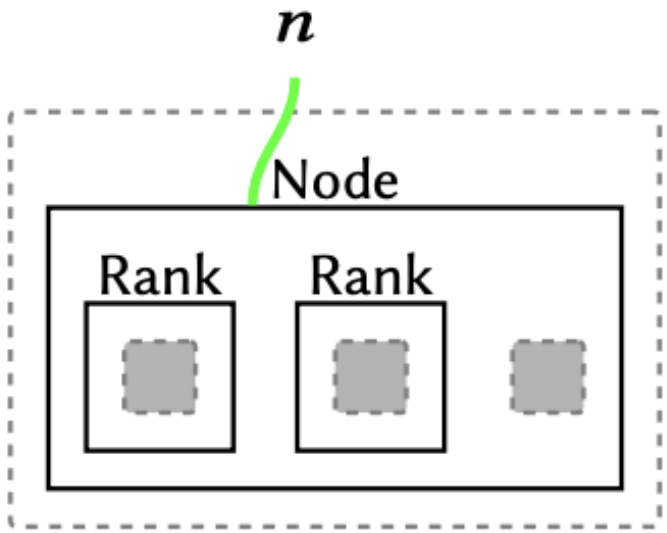
Model verification

We validate our model by checking:

- All nodes eventually join the DAG
- Nodes join with the optimal rank
- DAG is cycle-free



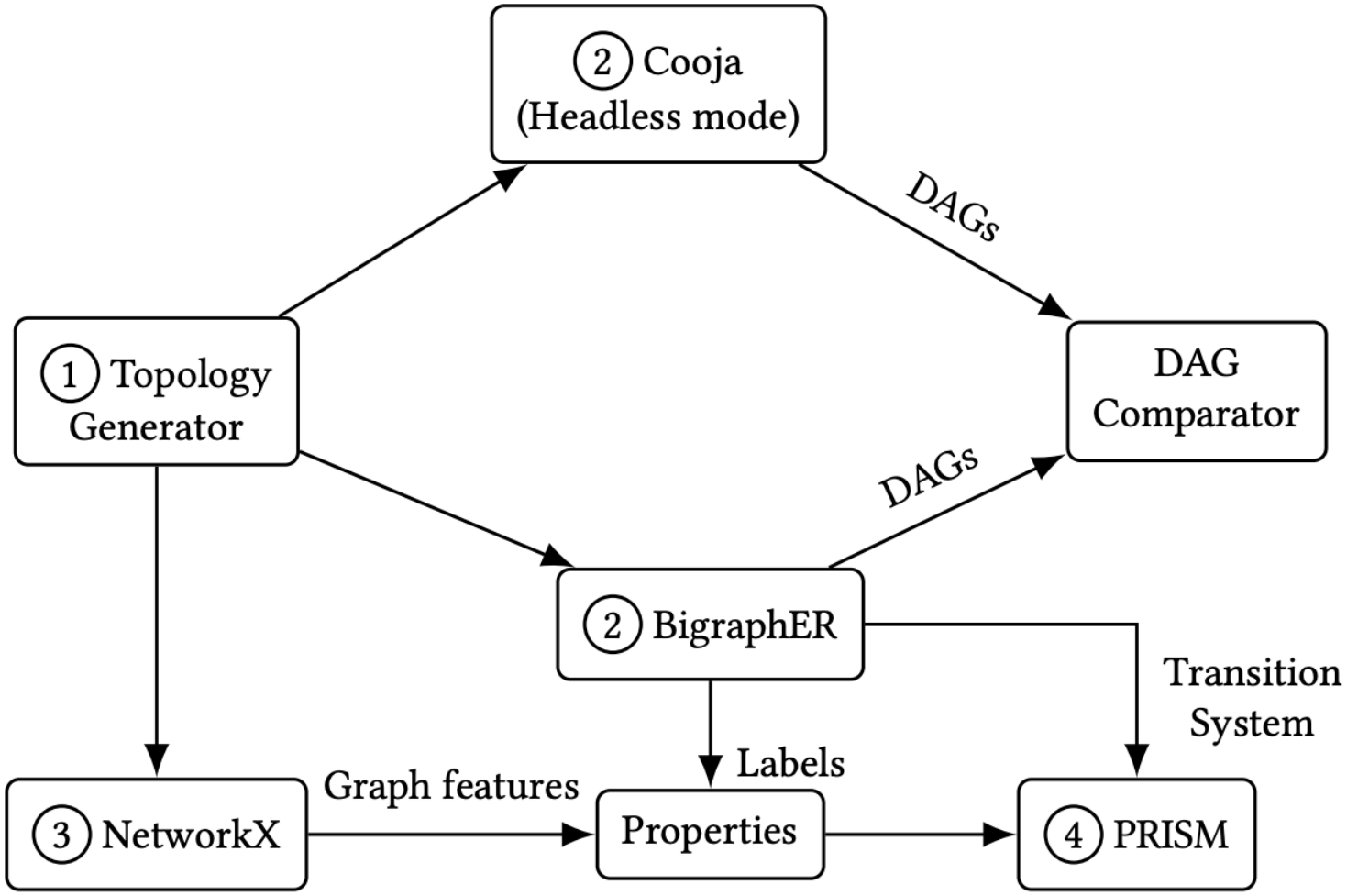
We use BigraphER to generate the labelled transition systems and PRISM to check the properties of a network topology

$$\mathbf{A}[\mathbf{G}\neg\texttt{multijoin}]$$

Experimental comparison

We compare our approach against simulation

- Cooja is a popular emulator for IEEE 802.15.4 networks
- 100 randomly generated network topologies with between 7 and 9 nodes



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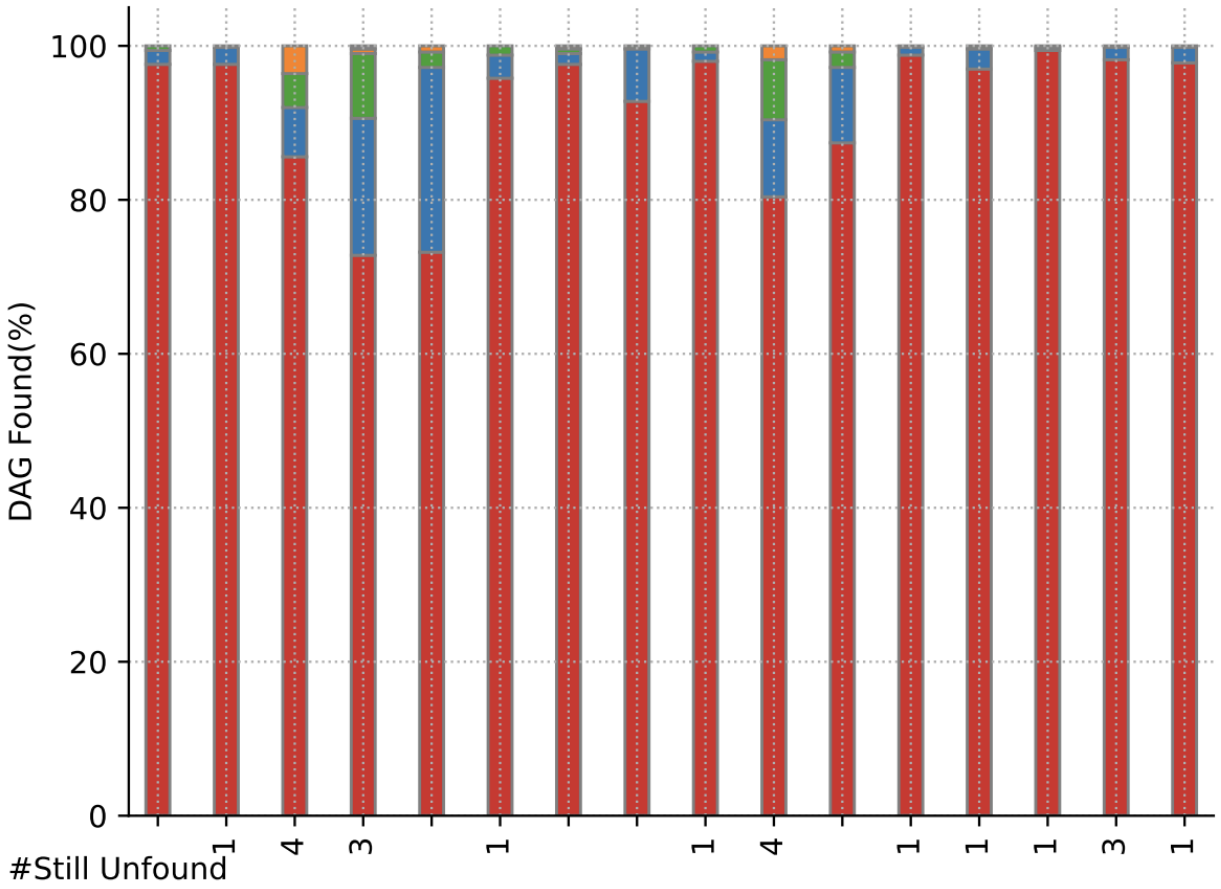
Results: coverage is the main difference

The bigraph model identifies all the valid DAGs for a topology

Cooja produces one DAG per run

- Several runs (500) needed to find multiple DAGs but still many misses
- Simulation outcomes depend on timing and heuristics



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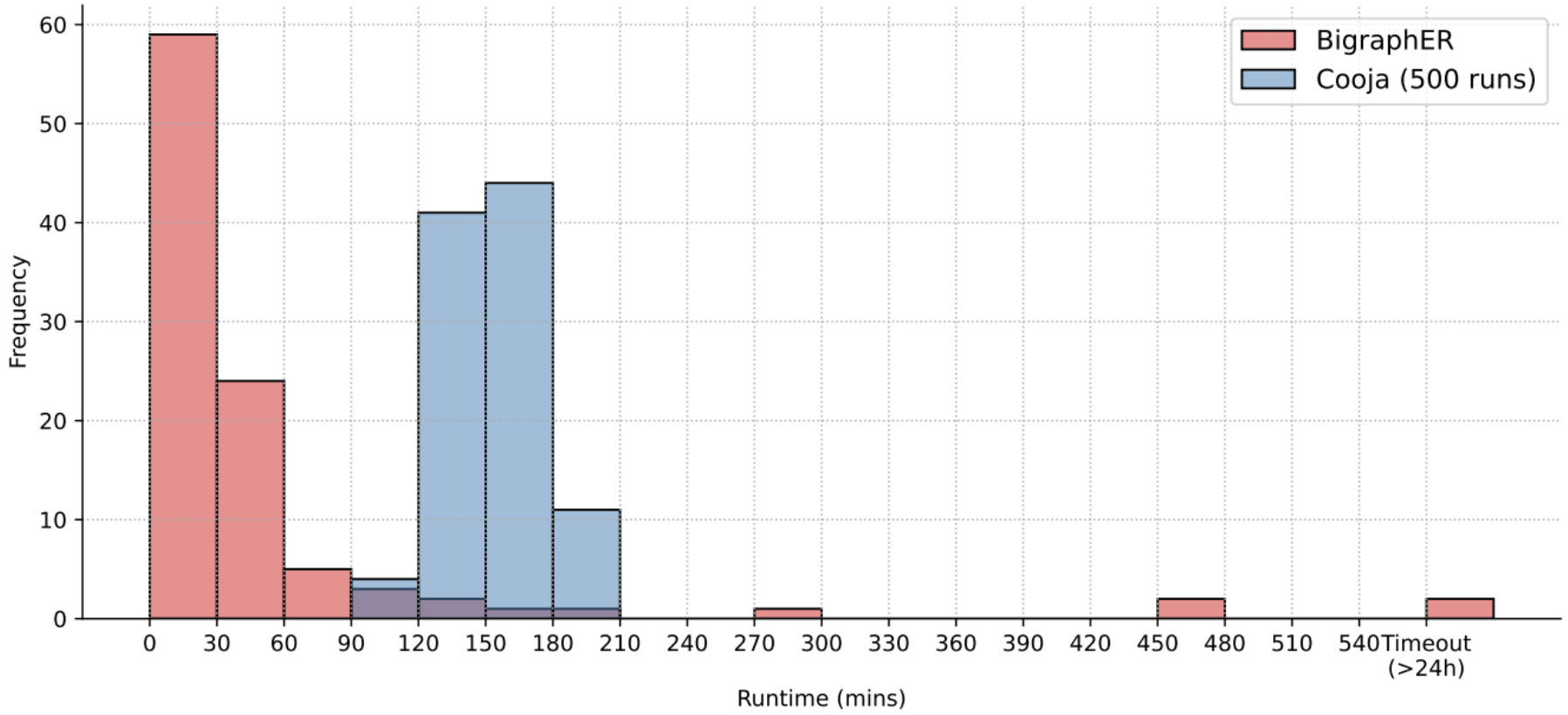
Results: running times

Comparable performance for the analysed scale



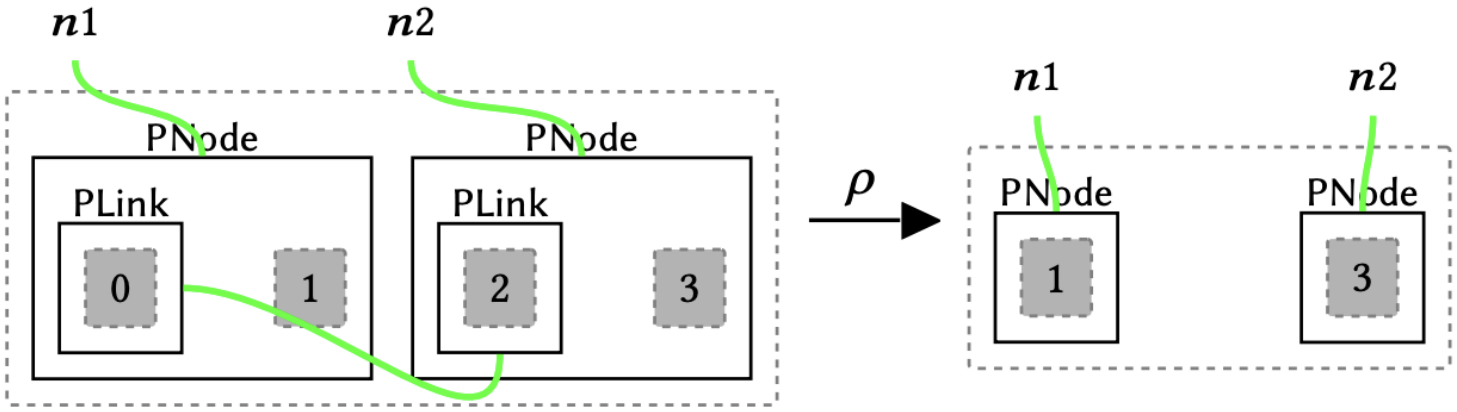
Extensibility

Low modelling overhead for design-space exploration

- Protocol variations as rule changes (add or modify reaction rules)
- Useful to explore behaviour before re-implementation

Examples:

- Adversarial behaviour
- Link instability



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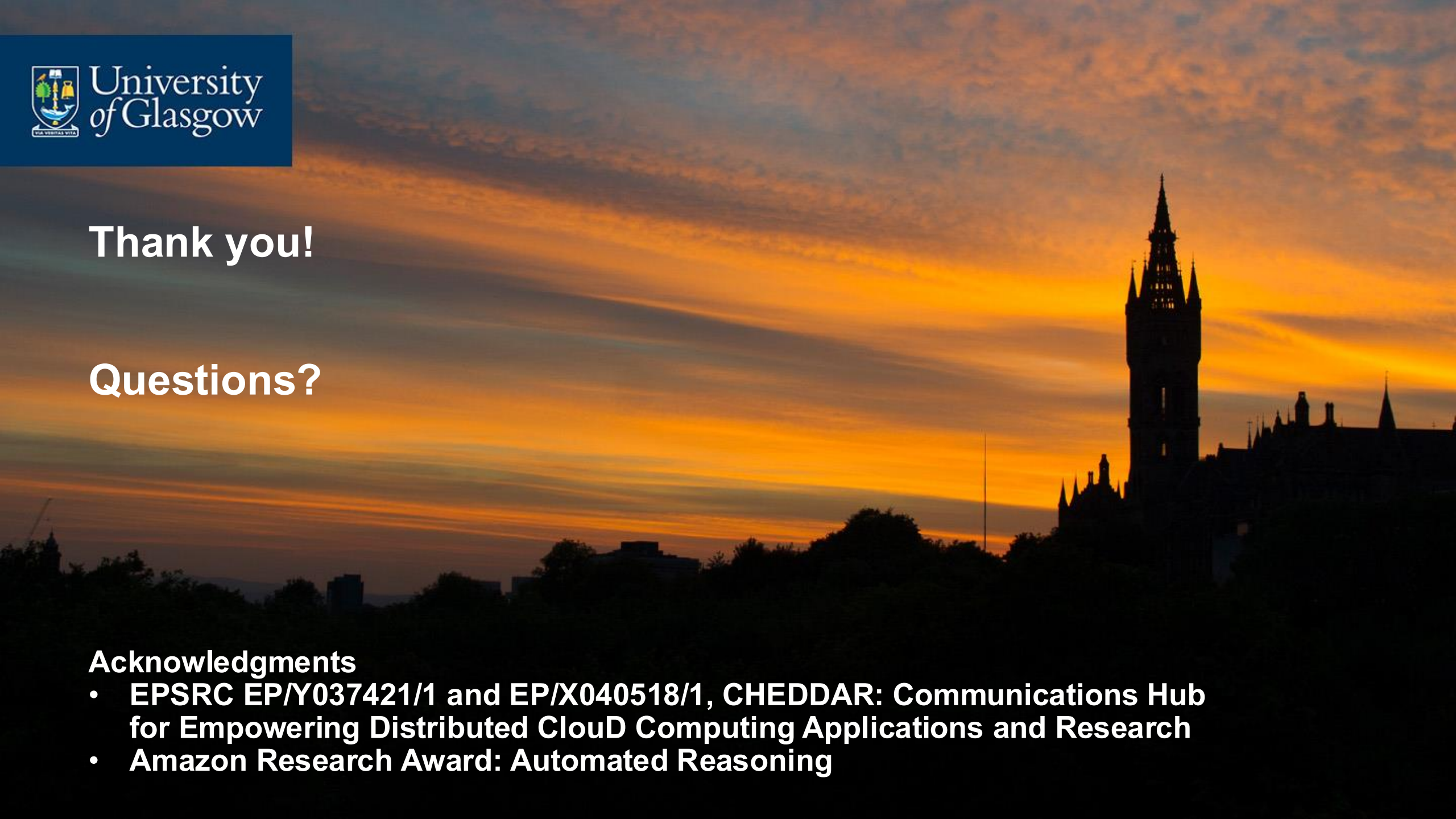
Conclusion

- Bigraphs give a diagrammatic but formal specification
- The model is executable via BigraphER
- Verification is performed using standard model checking tools
- Exhaustive analysis complements simulation
- Rule-based models support rapid iteration



Thank you!

Questions?

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