TECHNISCHE UNIVERSITÄT WIEN

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Emerging Synchrony in Applauding Audiences

Formal Analysis and Specification

Luca Di Stefano, Omar Inverso

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The Story So Far

From this... (2019)

PHOTO: AMIRHOSSEIN KHEDRI, UNSPLASH. ANIMATION: DE NICOLA, DI STEFANO, INVERSO (LINK)

The Story So Far

To this… (2022)

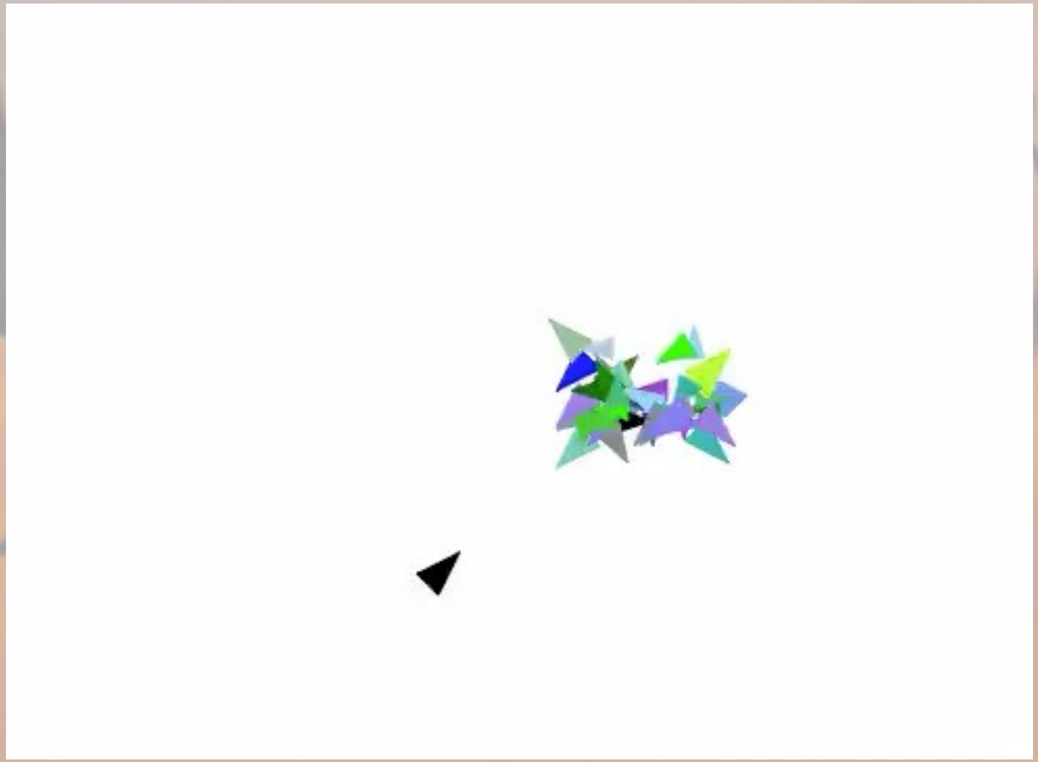


PHOTO: AMIRHOSSEIN KHEDRI, UNSPLASH. ANIMATION: DE NICOLA, DI STEFANO, INVERSO, VALIANI (LINK)

The Story So Far

…And this (2023)

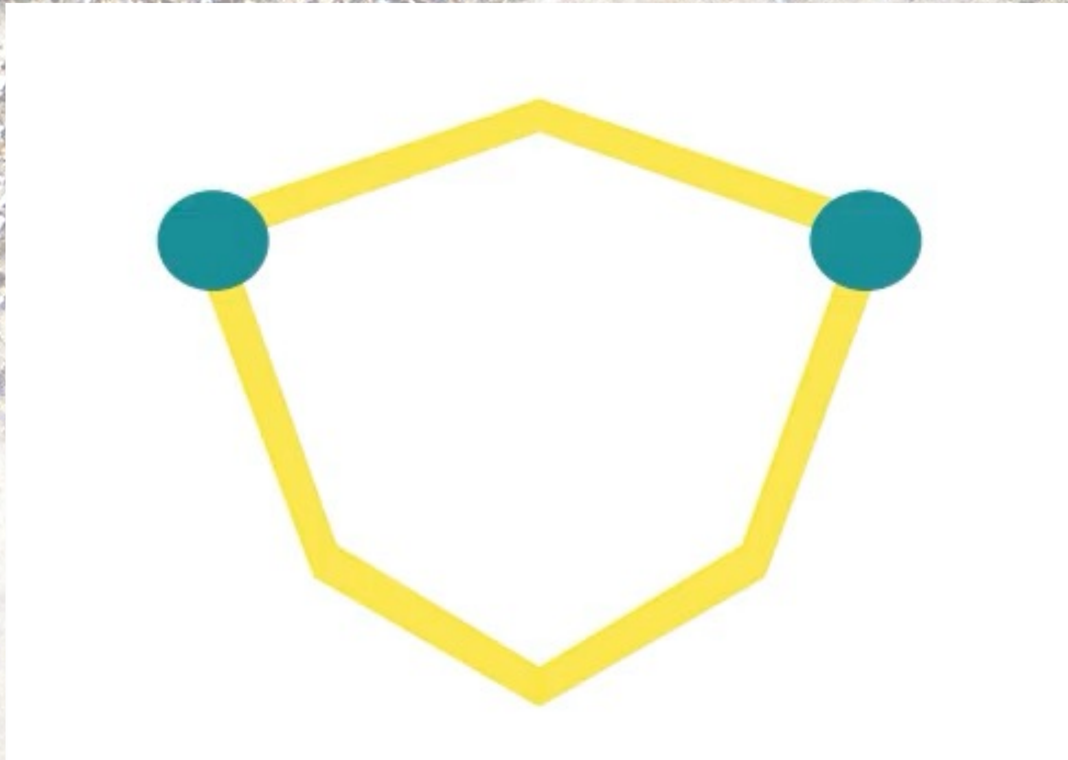


PHOTO: AMIRHOSSEIN KHEDRI, UNSPLASH. ANIMATION: DE NICOLA, DI STEFANO, INVERSO, VALIANI (LINK)

Another Example of Collective Behaviour

SOURCE: HTTPS://WWW.YOUTUBE.COM/WATCH?V=AU5TGPPCPUS

Our Contributions

- Formal specification of a clapping audience
- (Minor extensions to the formal language we used)
- Simulation through an automated workflow
- Verification that convergence is stable (in our model)

Our Specification in a Nutshell

- Each agent claps at its own frequency
- Agents can listen to audience
- When many agents clap at the same moment…
- …Other agents can sense it…
- …and try to synchronise with that collective rhythm

LAbS

- Specification of collective adaptive systems
- Original focus:[1]
  - Virtual stigmergies (replicated key-value stores)
  - Attribute-based Communication
  - Shared memory was also allowed
- More recently: agents observe and react to exposed features (attributes)[3,4]

[1]De Nicola, Di Stefano, Inverso. Multi-agent systems with virtual stigmergy. Sci. Comput. Program. 20202

[2]De Nicola et al. Modelling flocks of birds and colonies of ants from the bottom up. STTT, 2023

[3]De Nicola et al. Intuitive Modelling and Formal Analysis of Collective Behaviour in Foraging Ants. In CMSB’23

Modelling Challenges

- LAbS assumes one action per time step, but we have to model agents that act at the same time (similar to cellular automata)
  1. Restrict interleaving (rounds with 1 action per agent)
  2. Store “intermediate” state updates separately

- Allow an agent to count how many agents of type T satisfy φ (e.g., how many are clapping right now):

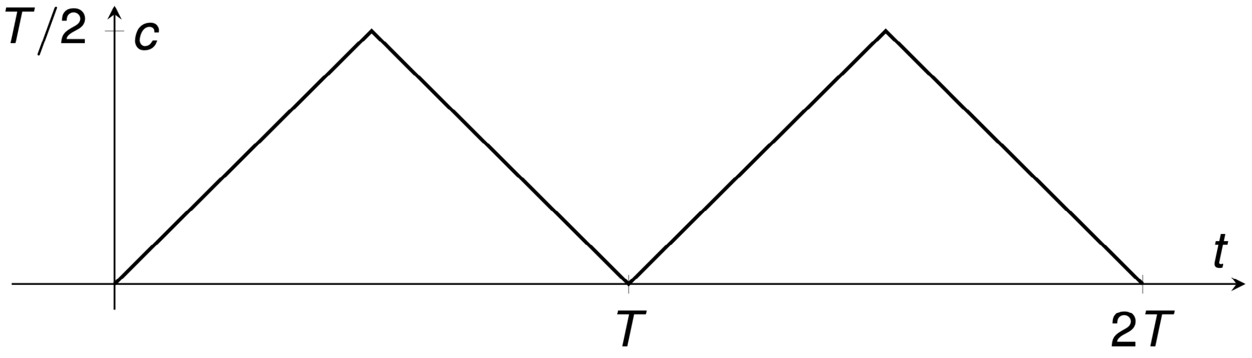
$$result := \mathbf{count}\ \mathrm{T}\ x, \varphi(x)$$

Individual Clapping

- T clapping period
- c counter variable: when 0, the agent is clapping
- $sign$ whether *c* should increase or decrease

Repeat forever:

$$sign := \textbf{if } c = 0 \textbf{ then } 1 \textbf{ else}$$
$$\textbf{if } c = T/2 \textbf{ then } -1 \textbf{ else } sign$$
$$c := c + sign$$



Listening

- Check how many agents are clapping
- Use a threshold value to distinguish loud moments
- Track the time interval θ between loud moments

$$
\begin{aligned}
&audienceClap := \textbf{count}\ \mathrm{Agent}\ i, c_i = 0 \\
&\theta := \ \textbf{if}\ audienceClap \geq loud\ \textbf{then}\ 0\ \textbf{else}\ \theta + 1
\end{aligned}
$$

Adaptation

- After 2 loud moments, agents can compare their own T with the time interval θ between them
- New T = average of old T and θ
- (Bounded by parameters *Tmin*, *Tmax*)

$$T := (T + \theta) / 2$$
$$T := \min(\max(Tmin, T), Tmax)$$

Other adaptation mechanisms (see our paper!)
• Lower loudness threshold if loud moments are too few • Increase loudness threshold if loud moments are many • If $T = \theta$ and agent not in sync, adjust phase

Experimental Setting

	Name	Meaning	Initial value(s)
Variables	T	Clapping period	$Tmin, \dots, Tmax$
	c	Clapping counter	$1, \dots\ T/2$
	$sign$	How c should be updated	1
	$loud$	Loudness threshold	$loud^{(0)}$
	θ	Time interval between loud moments	$-\infty$
Parameters	N	Number of agents	16
	$Tmin$	Minimum value for T	8
	$Tmax$	Maximum value for T	20
	$loud^{(0)}$	Initial loudness threshold	4

SLiVER[1] for SAT-based Simulation

- LAbS specification ⇒ sequential C program[2]
- Use off-the-shelf verification tools for C
- SAT-based BMC + Nondet heuristics + assertion that is violated after *B* steps = random execution traces

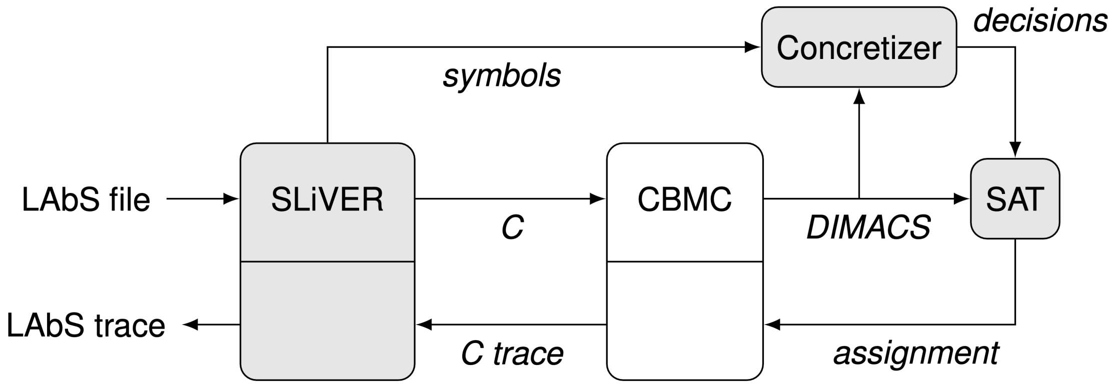
Problem
• Tool encodes nondeterministic state by **symbolic variables** (for verification purposes) • Decision **not efficient**, esp. with nondet heuristics

[1]https://github.com/labs-lang/sliver

[2]Di Stefano, De Nicola, Inverso. Verification of Distributed Systems via Sequential Emulation. TOSEM, 2022

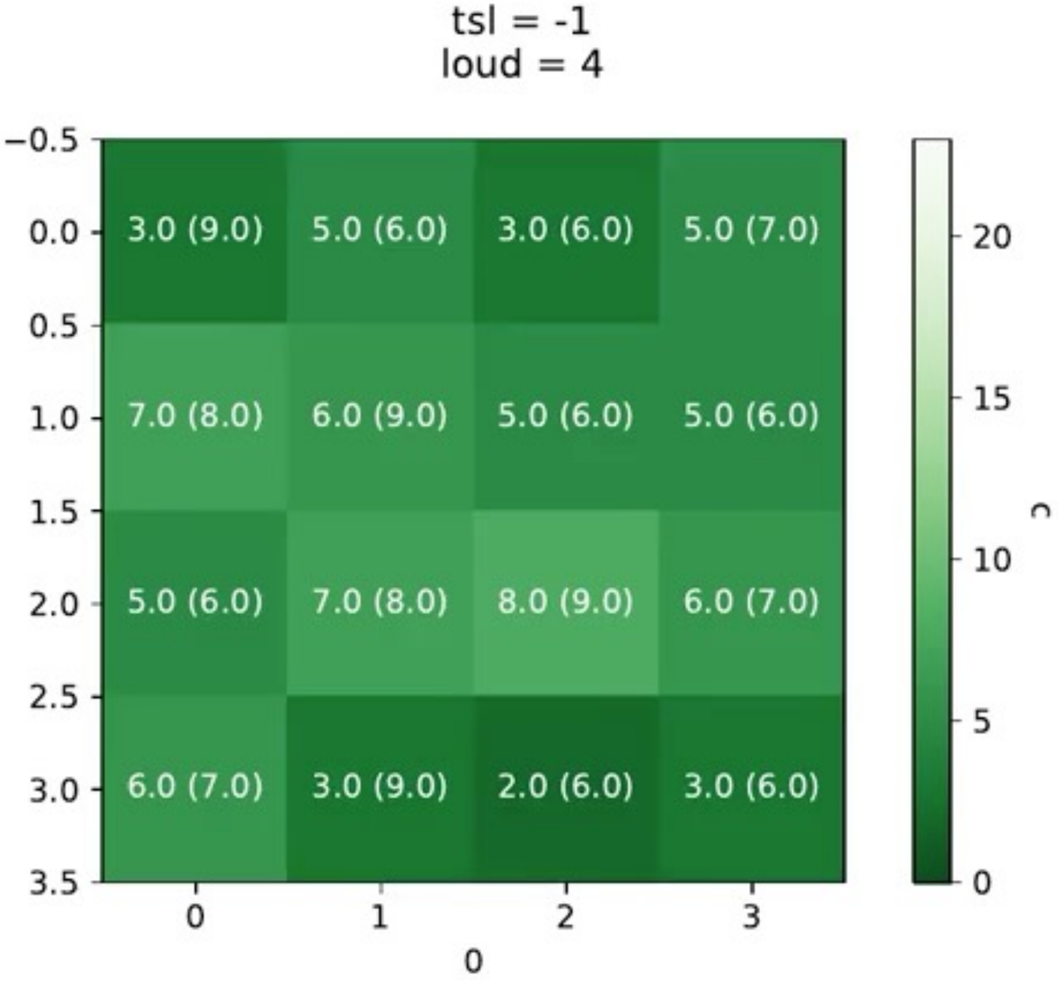
Concretization

- Simulation: no need to explore multiple initial states
- Tell SAT to use one (random) value for each variable
- Still allow SAT to backtrack
- (Applicable to any nondet variable that can be guessed statically)



(Gray=components we built or modified)

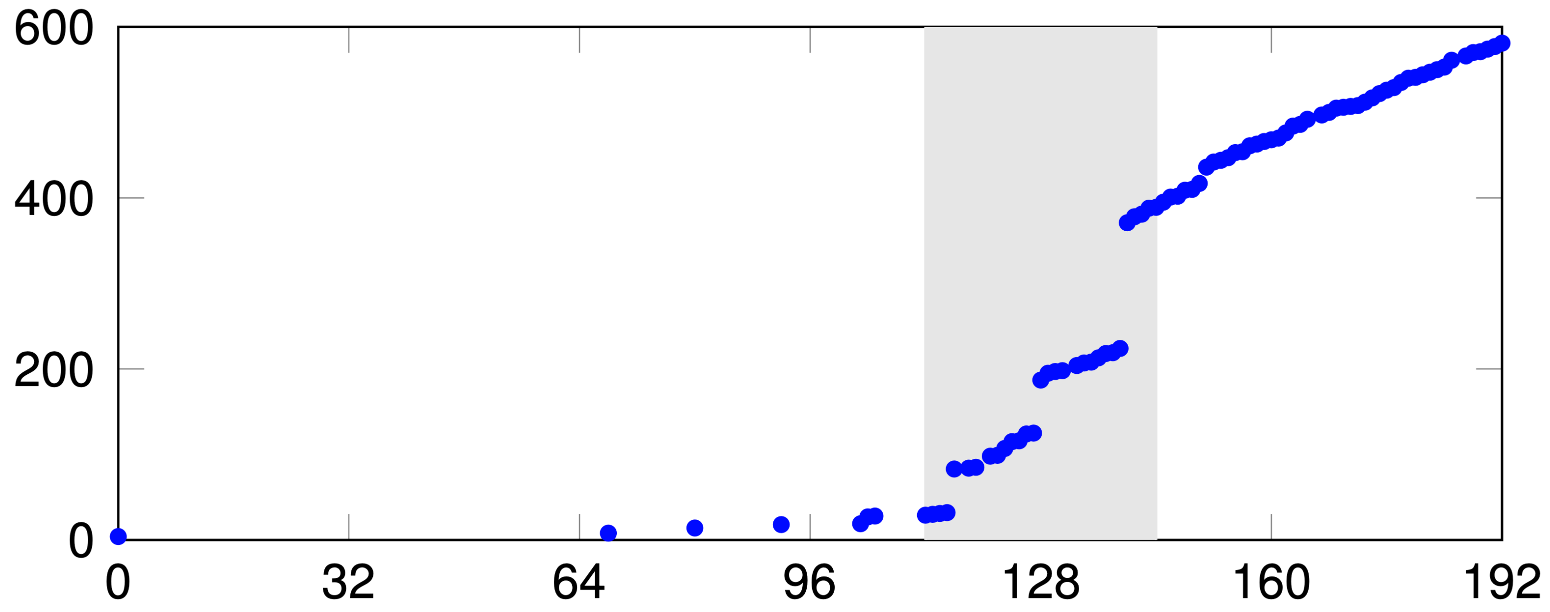
A Sample Simulation



AVAILABLE AT HTTPS://DOI.ORG/10.5281/ZENODO.11374963

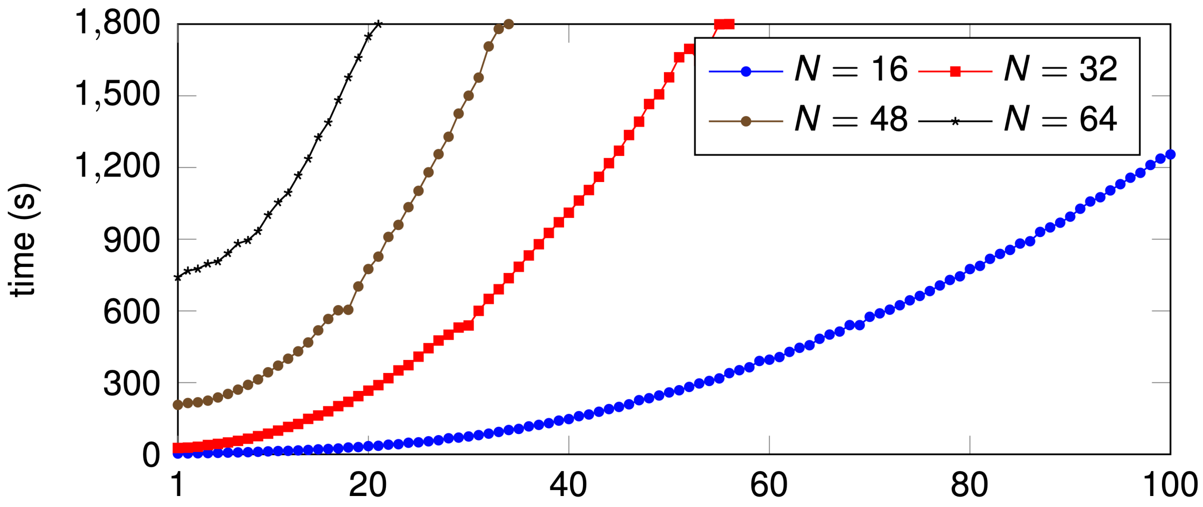
Emergence of Synchronous Applause

- 1000 simulations, 192 steps each
- 58% synchronise before the end of the trace
- “Phase transition” around 128 time steps



Stability of Synchronous Applause

- Can our agent break synchrony after reaching it?
- BMC, increasing bound, assuming audience in synchrony at time 0
- We stop at bound=100 or after timeout (30')
- No violations observed ⇒ stable synchrony



Conclusion

- We presented a first attempt at formal modelling of a clapping audience
- Mix of simulation and verification to analyze its emergent behaviour
- Formal approach to CAS modelling has several benefits
  - High-level formalisms
  - Intuitive specifications
  - Access to efficient analysis techniques

… As pointed out by Rocco in countless occasions ☺
AbC, CARMA, DReAM, KLAIM, SCEL, … (and LAbS!)

Future Work

- Improve simulation performance
- Improve range of supported properties for verification
- Data-driven approaches
  - Given one or more traces of a system S
  - Write a LAbS model M
  - Does M allow (all, most, some) of the traces from S?
- (Do you have interesting case studies? ☺)