A Logical Framework for Self-Optimizing Networked Cyber-Physical Systems

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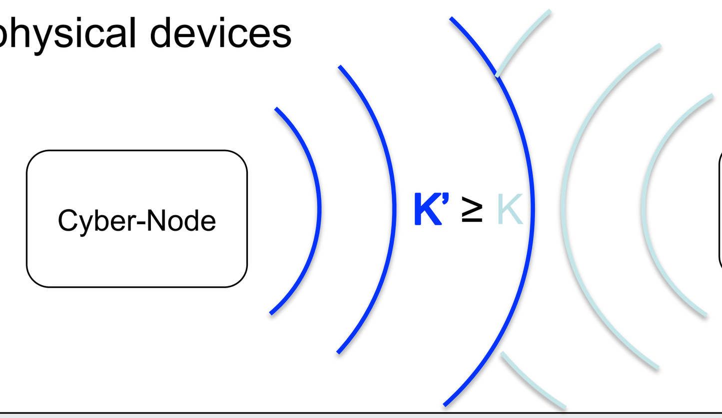
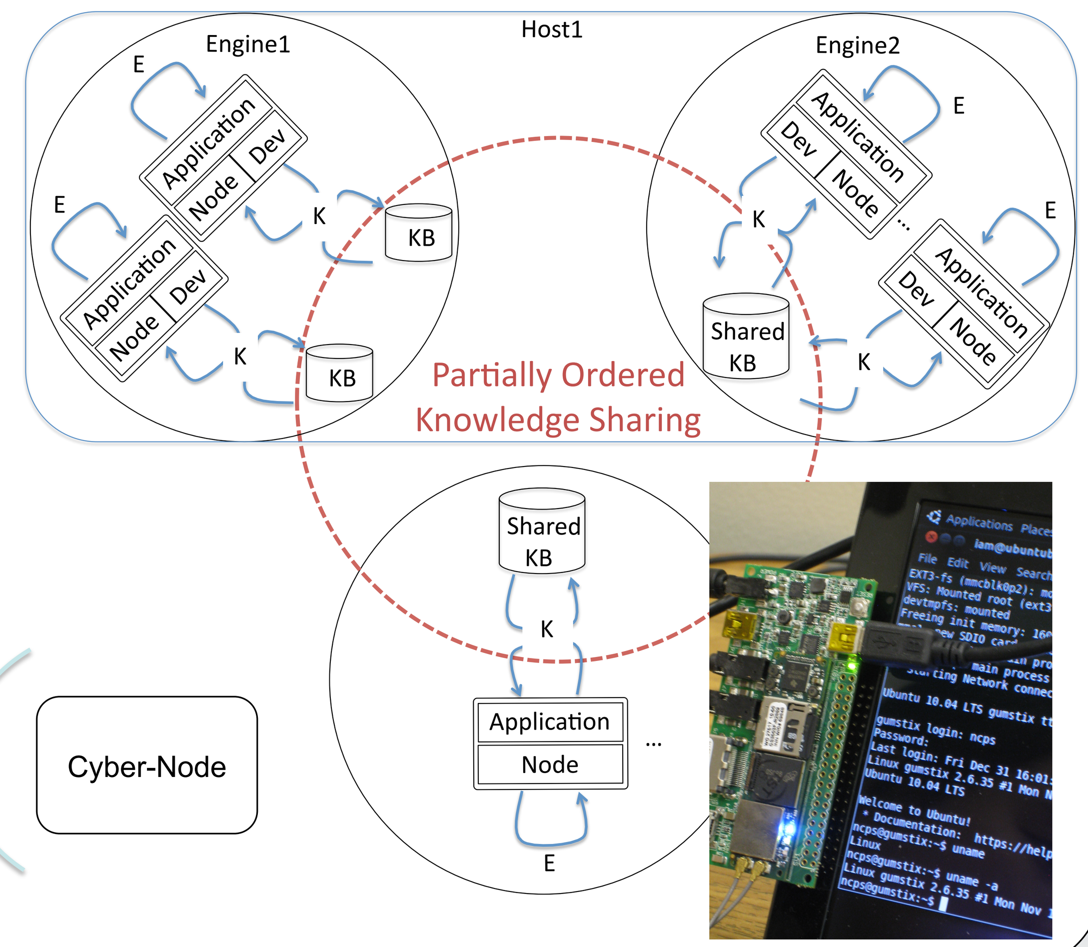
An Application Framework for Networked CPS

- Based on new loosely-coupled distributed computing model:
  Partially Ordered Knowledge Sharing
- Inspired by our earlier work on delay-/disruption-tolerant networking (DTN)
- Minimal assumptions on network connectivity (can be very unreliable)
- Works with dynamic topologies, network partitions, and mobile nodes
- Designed for heterogeneous networking technologies and heterogeneous nodes
- Partial order allows the network to replace obsolete or subsumed knowledge
- Global consistency is not enforced (impossible in challenging environments)
- Avoids strong non-implementable primitives, e.g. transactions
- Locally each cyber-node uses an event-based model with local time
- Events are local, but knowledge can be shared and cached in the network
- Each cyber-node can have attached cyber-physical devices
- Framework supports
  - model-based simulation
  - probabilistic analysis algorithms
  - real-world deployment/execution
  - visualization of simulated NCPS



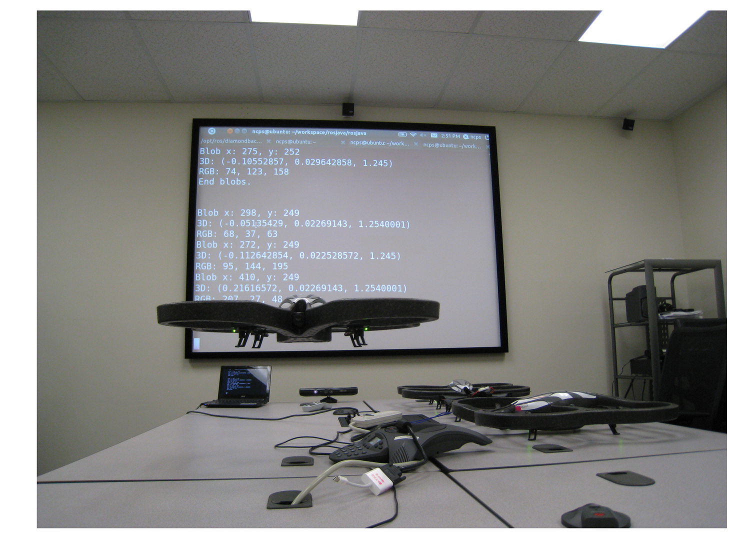


Networked Quadricopter Testbed

- Quadricopters are a very interesting class of cyber-physical devices (equipped with many sensors and actuators including cameras)
- Networked quadricopters will allow us to perform collaborative tasks (e.g. formation flying, distributed sensing, monitoring)
- Quadricopters (and their components) become devices in the cyber-application framework
- Currently controlled from a network of netbooks on the ground (each node can control one or multiple quadricopters)
- Can be equipped with gumstix SBC and additional devices (e.g. GPS, digital compass) for more autonomy
- Currently experimenting with vision-based localization for indoor-usage (see pictures below)

Four quadricopters before the launch

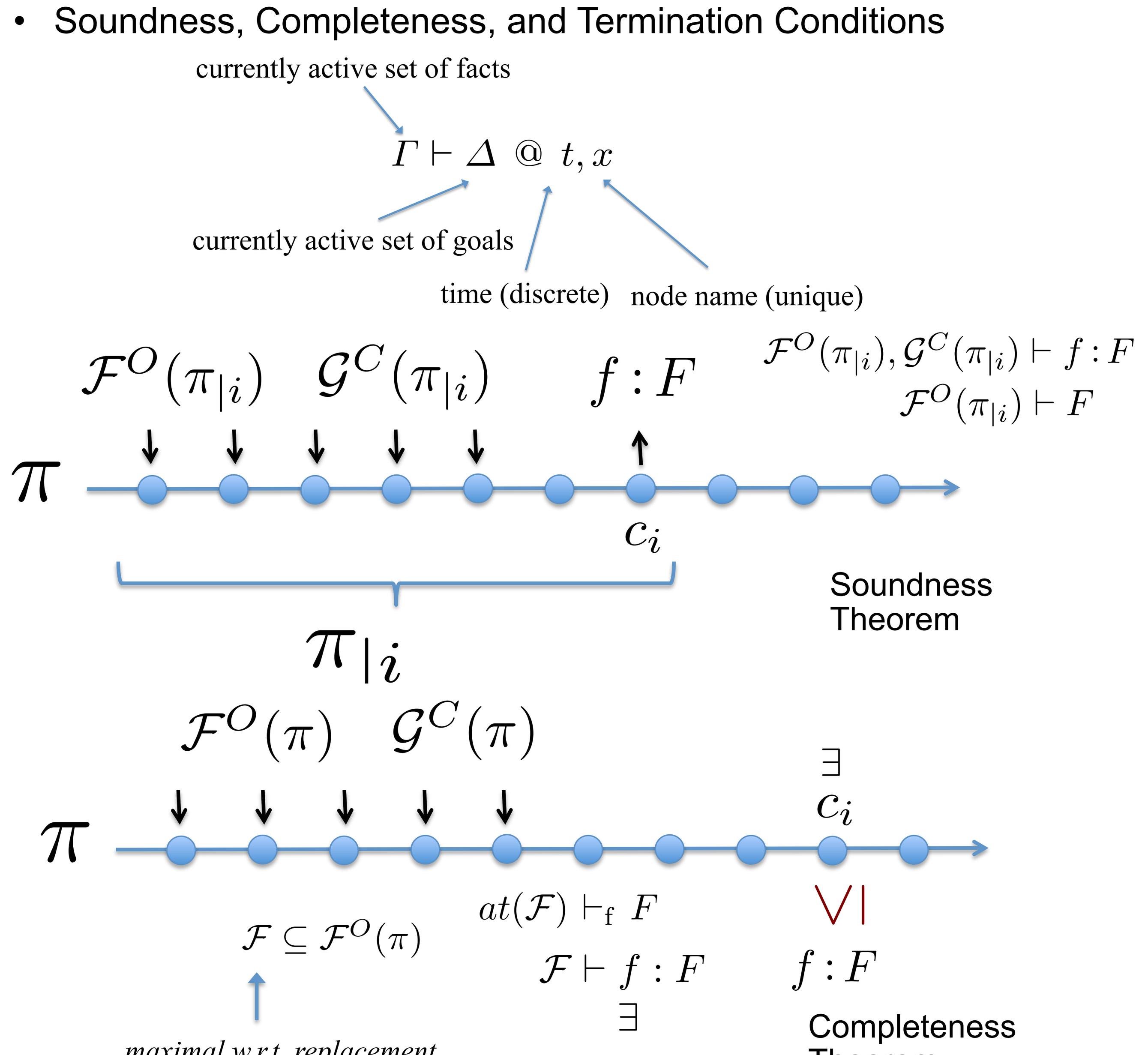
Four quadricopters controlled by the cyber-application framework



Vision-based localization experiment (utilizing Kinect 3D camera)

Distributed Logic for Declarative Control

- Truly distributed logical framework with explicit proof objects
- Cyber-predicates enable interaction with the physical world
- Facts and goals treated on an equal footing
- Covers entire spectrum between autonomy and cooperation
- Tested with abstract mobility model and Stage multi-robot simulator
- Soundness, Completeness, and Termination Conditions



$$\frac{\Gamma \vdash \Delta \ @ \ t, x}{\Gamma \vdash \Delta, \mathtt{C}(G) : G \ @ \ t', x} \quad \text{if } G = p_c(t, \ldots) \text{ is a cyber-goal} \qquad \text{(Control)}$$

$$\frac{\Gamma \vdash \Delta \ @ \ t, x}{\Gamma, \mathtt{O}(F) : F \vdash \Delta \ @ \ t', x} \quad \text{if } F = p_c(t, \ldots) \text{ is a cyber-fact} \qquad \text{(Observation)}$$

$$\frac{\Gamma, f : F \vdash \Delta \ @ \ t, x}{\Gamma \vdash \Delta \ @ \ t', x} \quad \text{if } f : F \prec \Gamma, \Delta \qquad \text{(Replacement1)}$$

$$\frac{\Gamma \vdash \Delta, g : G \ @ \ t, x}{\Gamma \vdash \Delta \ @ \ t', x} \quad \text{if } g : G \prec \Gamma, \Delta \qquad \text{(Replacement2)}$$

$$\frac{\Gamma_x \vdash \Delta_x \ @ \ t_x, x \quad \Gamma_y, f : F \vdash \Delta_y \ @ \ t_y, y}{\Gamma_x, f : F \vdash \Delta_x \ @ \ t'_x, x} \qquad \text{(Communication1)}$$

if $x \neq y$, $t'_x \geq t_y$, and $f : F$ is fresh at x.

$$\frac{\Gamma_x \vdash \Delta_x \ @ \ t_x, x \quad \Gamma_y \vdash \Delta_y, g : G \ @ \ t_y, y}{\Gamma_x \vdash \Delta_x, g : G \ @ \ t'_x, x} \qquad \text{(Communication2)}$$

if $x \neq y$, $t'_x \geq t_y$, and $g : G$ is fresh at x

$$\frac{\Gamma \vdash \Delta, g : G \ @ \ t, x}{\Gamma, \mathtt{B}_\sigma(g) : \sigma(G) \vdash \Delta, g : G \ @ \ t', x} \qquad \text{(Built-in)}$$

if G is a built-in goal with a solution $\sigma(G)$ such that $\mathtt{B}_\sigma(g) : \sigma(G)$ is fresh.

$$\frac{\Gamma, f_1 : \sigma(P_1), \ldots, f_n : \sigma(P_n) \vdash \Delta \ @ \ t, x}{\Gamma, f_1 : \sigma(P_1), \ldots, f_n : \sigma(P_n), f : \sigma(Q) \vdash \Delta \ @ \ t', x} \qquad \text{(Forward1)}$$

if $l : P_1, \ldots, P_n \Rightarrow Q$ is a clause from Ω_{f},
$f = l_\sigma(f_1, \ldots, f_n)$, $\sigma(Q)$ is a fact, and $f : \sigma(Q)$ is fresh.

$$\frac{\Gamma, f_1 : \sigma(P_1), \ldots, f_{j-1} : \sigma(P_{j-1}) \vdash \Delta \ @ \ t, x}{\Gamma, f_1 : \sigma(P_1), \ldots, f_{j-1} : \sigma(P_{j-1}) \vdash \Delta, g : \sigma(P_j) \ @ \ t', x} \qquad \text{(Forward2)}$$

if $l : P_1, \ldots, P_n \Rightarrow Q$ is a clause from Ω_{f},
$g = l_\sigma^{-1}(f_1, \ldots, f_{j-1})$, $\sigma(P_j)$ is a goal, and $g : \sigma(P_j)$ is fresh.

$$\frac{\Gamma, f_1 : \sigma(P_1), \ldots, f_n : \sigma(P_n) \vdash \Delta, g' : G' \ @ \ t, x}{\Gamma, f_1 : \sigma(P_1), \ldots, f_n : \sigma(P_n), f : \sigma(Q) \vdash \Delta, g' : G' \ @ \ t', x} \qquad \text{(Backward1)}$$

if $l : P_1, \ldots, P_n \Rightarrow Q$ is a clause from Ω_{b},
$f = l_\sigma(f_1, \ldots, f_n; g')$, $\sigma(Q) = \sigma(G')$, $\sigma(Q)$ is a fact, and $f : \sigma(Q)$ is fresh.

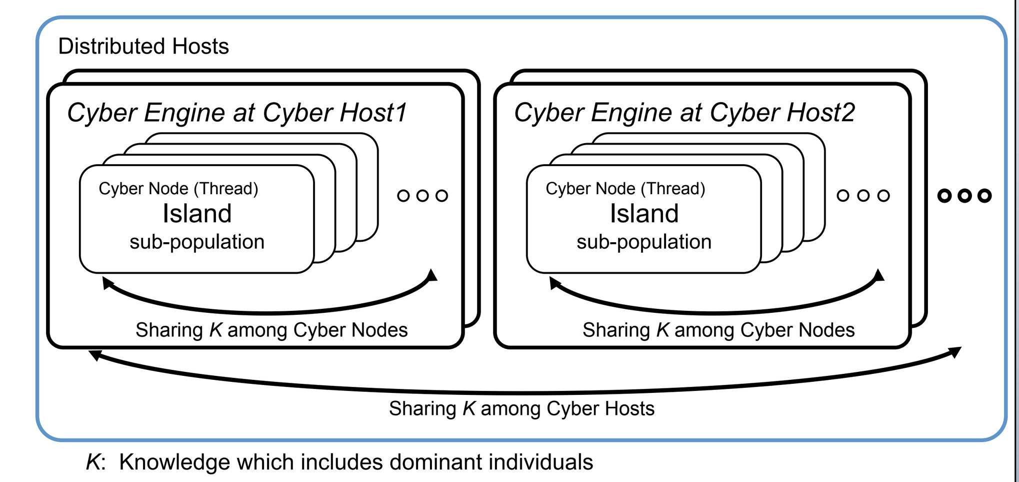
$$\frac{\Gamma, f_1 : \sigma(P_1), \ldots, f_{j-1} : \sigma(P_{j-1}) \vdash \Delta, g' : G' \ @ \ t, x}{\Gamma, f_1 : \sigma(P_1), \ldots, f_{j-1} : \sigma(P_{j-1}) \vdash \Delta, g' : G', g : \sigma(P_j) \ @ \ t', x} \qquad \text{(Backward2)}$$

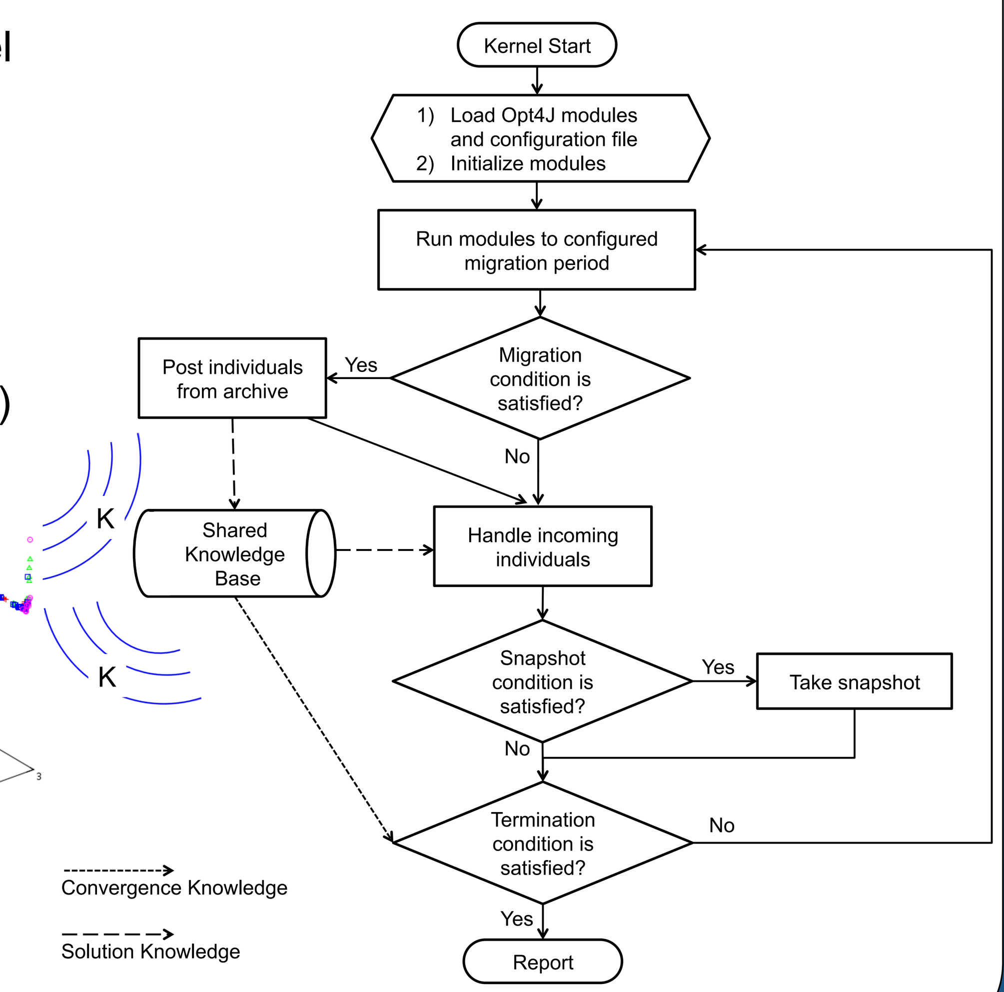
if $l : P_1, \ldots, P_n \Rightarrow Q$ is a clause from Ω_{b},
$g = l_\sigma^{-1}(f_1, \ldots, f_{j-1}; g')$, $\sigma(Q) = \sigma(G')$, $\sigma(P_j)$ is a goal, and $g : \sigma(P_j)$ is fresh.

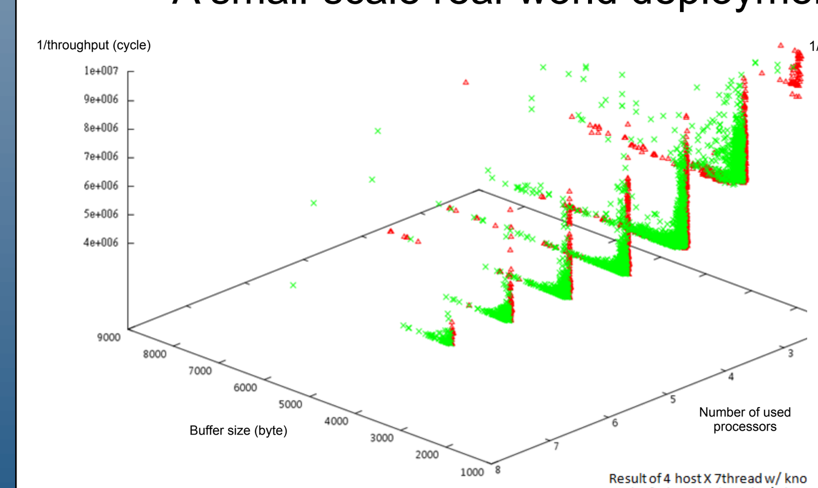
$$\frac{\Gamma \vdash \Delta \ @ \ t, x}{\Gamma \vdash \Delta \ @ \ t', x} \qquad \text{(Sleep)}$$

Parallel and Distributed Optimization

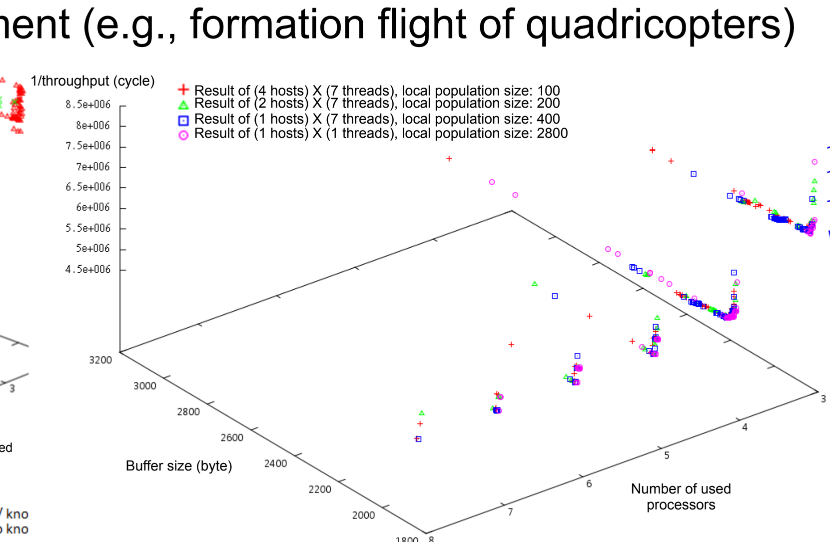
- Distributed and parallel meta-heuristic framework combining
  - an existing mature sequential optimization framework (Opt4J) with
  - a loosely coupled distributed island model for scalable parallelization
- The parallelism is transparently provided by the cyber-framework
  - cyber-nodes cooperate by emitting waves of knowledge, which interfere until all local solutions asynchronously converge to a global solution
- Optimization fits well into the partially ordered knowledge-sharing model
- Replacement order is defined by either
  - single objective function (solution fitness) or
  - multiple objective functions (Pareto optimality)
- Algorithm: population based meta-heuristic optimizer utilizing the island model
- Case study: design space exploration of an embedded multimedia system
- Key features: scalability and robustness in the optimization problem
- Optimizer performance is studied on Internet-wide testbed (Planet Lab)
- Possible next steps:
  - Combining optimization and declarative control
  - Use of weighted/quantitative/probabilistic logic
  - A small-scale real-world deployment (e.g., formation flight of quadricopters)







Knowledge-sharing leads to better solutions within a limited time.



Solutions from parallel and sequential execution represent similar quality.