Fraglets
Stochastic Programming for Provable Program Dynamics and Self-Healing Programs

or

"Programming by Equilibria"

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Content

• Programming by Equilibrium
  Dynamical aspects of program execution in Fraglets

  • Stochastic reaction scheduler

  • Deterministic prediction of the program dynamics

• Self-Healing Programs

• Example: A Self-Healing Load Balancing Protocol
A Distributed Computation Example in Fraglets

Consider the following distributed Fraglets program:
Shuttle-Service fraglets randomly send X-fraglets to a neighbor node.
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What happens to the number of X-fraglets in each node? This depends on how the reactions are scheduled!
ASAP Scheduler

• ASAP Scheduling: Each node executes reactions as fast as possible.

• Result: X-molecules **drift to nodes with high degree:**

• How does nature “schedule” chemical reactions?
Chem. Scheduler ↔ Stochastic Molecule Collisions

- **Statistical Mechanics**: *Prevalent molecules ⇒ more frequent collisions.*
  
  In a reaction vessel of constant volume, the collision frequency increases with a higher mol. density.

- **Stochastic scheduling algorithm**: [Gibson&Bruck, 2000]
  
  - For each reaction $A + B \rightarrow C$, calculate the reaction interval
    
    $$
    \tau \sim \text{Exp} \left( \frac{1}{x_A x_B} \right)
    $$

    $x_A, x_B$ : number of A, B molecules; randomness due to Brownian motion.

  - Sort the next reaction time of all reactions into a priority queue.

  - **Wait** for the next reaction time.

  - Execute that reaction and calculate its next reaction interval.
Chem. Scheduler ⇒ Equilibrium

- Chemical Scheduler: Each node **sleeps** for a well-defined (but inherently stochastic) time between two reactions.
- Result: The distributed reaction network strives for an **equilibrium** in which a numerical result is present:
  Each node contains the same averaged number of initial X-molecules.
Stochastic Execution → Deterministic Prediction

- External observer: Due to the random reaction intervals, the observer cannot predict which reaction is next and when it will occur.

- But we can approximate the macroscopic dynamic behavior:

- Macroscopically, all reactions obey the **Law of Mass Action:**
  
  The reaction rate is proportional to the reactant concentrations; e.g. the rate of a reaction $A + B \rightarrow C$ is $r = x_A x_B$

- This allows us to use **ordinary differential equations** to describe the reaction dynamics.

- **Convergence proof** for our distributed averaging algorithm:
  
  - Create the ODEs from the reaction network: $\dot{x} = Nr$
  
  - Find the fixpoint: $\vec{x} \equiv 0$

  - Determine whether the fixpoint is stable (perturbation analysis)
Self-Healing Programs

- The traditional approach: An infinite hierarchy of healers

- Our “chemical” approach avoids infinite regression:
  - The system shall monitor and \textit{repair itself}.
  - Goal: \textbf{Code Homeostasis}: The system continuously regulates its internal composition to maintain a stable state.
Self-Healing Programs - Growth

• In the first talk we presented the duplicating Quine.

• When scheduled by the Chemical Scheduler, the population of Quines exhibits exponential growth:

![Graph showing exponential growth](image-url)
Self-Healing Programs - Finite Reactor

- We limit the capacity (number of molecules) of the reaction vessel... Due to limited resources, we cannot let the population of Quines grow infinitely.

- ...by randomly destroying molecules when this vessel capacity is exceeded.

- This adds selective pressure to the population of molecules: Only molecules that continuously replicate themselves are able to “survive”.
Programs Recover From Code Deletion Attacks

- Even when removing 80% of the \([\text{matchp } x \ldots]\) or the \([x \ldots]\) molecules...

- ... the system finds back to equilibrium.
A Self-Healing Load-Balancing Protocol

- Goal: Balance packet stream from node src to node dest over two links.
- Node src uses of two competing Quines to send data packets to node dest.

- The Quines only replicate when receiving an acknowledgment.
- If path p2 drops packets, the replication rate of Quine 2 decreases:
  - The relative concentration of Quine 1 increases; it forwards more packets.
Conclusions

• A chemical, instead of ASAP, scheduling enables emerging equilibria.

• The solution to a computation is represented as an equilibrium of a dynamic system.

• Since there is no distinction between code and data: Code can be brought to equilibrium, i.e. software becomes self-healing.

• Application fields: continuously running (distributed) processes where an equilibrium represents the ideal situation/solution: e.g.
  • Routing protocols,
  • Flow control of data traffic,
  • Robotics,
  • Topological self-organization of sensor/actor networks, and reactive systems in general
Questions?
Backup Slides
Stochastic Scheduling and Deterministic Prediction

• Reactions are **NOT** executed as fast as possible

• Reactions are rather scheduled for a later time according to the **Law of Mass Action**:
  
  reaction rate = product of the reactant concentrations

**Reaction Network:**

**Differential Equation Approximation:**

\[
\frac{dx}{dt} = x
\]

**Exponential Growth of x w.r.t. Simulation Time:**

number of x molecules

time [s]

1 1/2 1/3 ...

matchp x for x x

2
Representation-Free Communication

- Comparison of how information is encoded in traditional and chemical networking protocols:

<table>
<thead>
<tr>
<th>Representation of local state information</th>
<th>Traditional Protocols</th>
<th>Chemical Protocols</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>symbolically:</td>
<td>abundance:</td>
</tr>
<tr>
<td></td>
<td>e.g. integers, flags</td>
<td>number of molecules</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Representation of exchanged information</th>
<th>Traditional Protocols</th>
<th>Chemical Protocols</th>
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<tbody>
<tr>
<td></td>
<td>symbolically:</td>
<td>rate-based:</td>
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<tr>
<td></td>
<td>encoded as symbols</td>
<td>the packet rate</td>
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<tr>
<td></td>
<td>inside packets</td>
<td>represents inform.</td>
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</tbody>
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Petri-Net Representation

- fixed number of queues
- different scheduling alg. (e.g. FIFO, EDF)
- traffic modeled as a Markov process

- var. number of substances
- a single scheduling alg. (Law of Mass Action)
- traffic and execution modeled as Markov proc.
Robustness of Quines to Deletion (qualitatively)
Robustness of Quines to Deletion (quantitatively)
Robustness of Quines to Deletion (quantitatively)

\[
\frac{\delta}{(\rho^2 + 2^* \#\text{quines})}
\]

- **Stable** region
- **Unstable** region

- Redundancy = 100
- Redundancy = 50
- Redundancy = 25

Injection rate \(\rho\) of \(x\) (w.r.t. virtual time)
Robustness of Quines to Mutation

- >95% valid results
- >50% valid results
- <50% valid results
- <5% valid results
- no result molecules
- inert
- infinite closure