SELF-ORGANIZATION IN THE HYPERVERSE

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PREFACE
Motivation

MMOGs

Second Life

Google Earth

The HyperVerse Project

- Distributed Virtual Environment (DVE) as Major Future Internet App
  - Immersive
  - Collaborative
  - Intuitive
- Assumptions ...
  - No pre-distributed Content
  - Lightweight Access
  - Federated Governance
  - Global-Scale
  - Self-Sustainable
A Self-Organizing Approach

- DVEs Great Domain for Self-Organization
  - High Dynamics
  - Spatial Context
- Inspiration from Physics, Biology, ...
  - Thermodynamics
  - Entropy
  - Statistical Mechanics
  - Epidemics
- This Talk
  - Three recent applications
**Flash Crowds ...**

- **Spontaneous Surge of Interest**
  - Hardly Predictable
  - Load Delays ...

- **Two Issues ...**
  - Data Provider Scalability
  - Data Consumer Fan-In

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**Provider Scalability**

- **Flash Crowd**
  - Numerous requestors for certain set of data

- **Peer-to-Peer Approach**
  - Utilize resources of requestors

- **HyperVerse**
  - BitTorrent-like distribution
  - Split data in chunks
  - Parallel retrieval from „nearby“ peers

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A Peer-to-Peer Approach

Scalability

Required Server Bandwidth
(with Torrents)

Required Server Bandwidth
(without Torrents)
Consumer Fan-In?

- What about Data Consumers?
  - Restricted Downlink
  - Fan-In Problem …
- Maybe there are 1,000 sources …
  - … but we can only use few in parallel

Load Delays

- Interest Management
  - Limited view of surrounding
  - When we know about objects, it might be too late to download data…
Simulation Results ...

(a) Visualization of Selected Steps

(b) Object Retrieval Traffic and Pending Data Units

Ideas?

- Aggregate View of Local Equilibria
Decentralized Flash Crowd Detection

- **Simple Per-Client Algorithm**
  - Mass = download complexity
  - Compute Center of Mass (CoM) of Local View
  - Compute Sum of Masses (SuM)

Epidemic Aggregation

- **Exchange CoM and SuM**
  - With random neighbor
  - In periodic interval
  - Maximum aggregation
- **Range-Constraint**
  - Lookahead radius

**Hoard**

- Enriched Local View of Clients
  - Use additional local information
  - Predict populated regions most probably entered
  - Hoard data speculatively

**Simulation**
Can this replace Interest Management as a whole?

Self-organized Adaptation of …
  • … Lookahead Radius
  • … Hoarding Rate
Till now ...
- Geometric Random Graph (GRG)
- Good for local gossiping and data retrieval

What about other characteristics?
- Routing of global messages
- Connectedness
- ...

Our Approach
- Additional statistically-structured Overlay with favorable characteristics
- Which characteristics?
Self-Adapting Thermodynamic Overlay Structures

**NETWORK PHASE TRANSITIONS**

**Phase Transitions in Physics**

![Diagram showing phase transitions in physics with Viscosity vs. Temperature graph. The graph has a sharp decrease in Viscosity at a certain temperature.]

- **Viscosity**
- **Temperature °C**

01.12.2008
Examples for Phase Transitions

- Small-World Property in Watts/Strogatz Graphs
- GCC in Erdös/Renyi Graphs
- Power Law Graphs

Critical Points in Power Law Graphs

- Vertex Degree Distribution
  \[ P(X = k) \propto k^{-\gamma} \]

- Moment
  \[ M_m = E(X^m) = \sum_{k=1}^{\infty} \frac{1}{k^{\gamma-m}} \]

- Convergence Interval
  \[ \gamma > m + 1 \]
Fundamental graph properties can be attributed to degree distribution exponent!
Application in P2P Networks

- Self-Organizing Power Law Overlay
  - Peers are aware of current phase
    - By monitoring degree distribution exponent
  - Peers actively initiate transition to other phase
    - By adapting degree distribution exponent
  - “Awareness-Driven Phase Transitions”

An Odd Analogy ...

- Body of Water = P2P system
  - Water molecule = Peer
- Awareness-driven Phase Transition
  - Depending on “application requirements”
  - Water molecules know and adapt current temperature
Decentralized Monitoring of the Power Law Exponent

Complications ...

- Reliable Power Law Fitting Non-Trivial
  - Maximum Likelihood Estimation (MLE)
  - currently best available method
  - See [Aaron Clauset 2007]

\[
\gamma = 1 + \frac{\sum_{v \in V} \ln \left( \frac{d_{cg}(v)}{d_{min} - \frac{1}{2}} \right)}{|V|}
\]
Estimating $d_{\text{min}}$

Minimize the following function ...

$$D(y) = \max_{x \geq y} \left| \left\{ v \in V : \deg(v) \geq x \right\} \right| P_y(X \geq x)$$

A Local Approach

- Local Knowledge = Own Vertex Degree
- Epidemic (Sum) Aggregation

$$(S_v, N_v) = (\ln(\deg(v)), 1)$$

Sum Aggregation

$$(S_v, N_v) \rightarrow \left( \sum_{w \in V} \ln(\deg(w)), |V| \right)$$
Local Estimation of $\gamma$

$$\gamma_v = 1 + \frac{N_v}{S_v - N_v \cdot \ln\left(d_{\min} - \frac{1}{2}\right)}$$

Local Estimation of $d_{\min}$

- **Restriction**
  - $d_{\min}$ among a fixed set of smallest vertex degrees
- **Again Epidemic Aggregation**
  - Of local vectors …

<table>
<thead>
<tr>
<th>MinDeg, []</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>deg(v)≥MinDeg, []</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>Count, []</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>...</td>
</tr>
</tbody>
</table>
Local Estimation of $d_{\text{min}}$

Minimize the following function ...

$$\bar{D}_y(y) = \max_{x \in \text{MinDeg}, x \geq y} \left| \frac{\text{Count}_v[x]}{\text{Count}_v[y]} - P_y(X \geq x) \right|$$

Evaluation Results

<table>
<thead>
<tr>
<th>Local Estimates</th>
<th>$i = 5$</th>
<th>$i = 10$</th>
<th>$i = 50$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$-Avg</td>
<td>2.833</td>
<td>2.833</td>
<td>2.833</td>
</tr>
<tr>
<td>$\gamma$-Var</td>
<td>$1.84 \cdot 10^{-2}$</td>
<td>$2.22 \cdot 10^{-4}$</td>
<td>$4.72 \cdot 10^{-17}$</td>
</tr>
<tr>
<td>$D$-Avg</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>$D$-Var</td>
<td>$4.1 \cdot 10^{-4}$</td>
<td>$7.31 \cdot 10^{-6}$</td>
<td>$1.50 \cdot 10^{-16}$</td>
</tr>
<tr>
<td>$d_{\text{max}}$-Avg</td>
<td>5.010</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$d_{\text{min}}$-Var</td>
<td>$6.850 \cdot 10^{-2}$</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 3. Average and variance of local power law parameter estimations for $i$ iterations of the proposed gossip scheme using a Min$_a$ and Min$C$, vector size of 10 entries. A global MLE power law fit of the graph used yields $\gamma = 2.833$, $d_{\text{min}} = 5$ and $D = 0.0497$. 
Adaptation of Power Law Exponent

- Monitoring of Power Law Exponent
  - Molecules can now efficiently retrieve global temperature
- Adaptation?
  - Instrumentation of Growth (e.g. Preferential Attachment)
  - Localized Preferential Reconnection Schemes

Open Issues

- Test for Power Law Property
  - How to be sure the network obeys a power law?
- Ignored Important P2P Requirement
  - Peers are not trustworthy
  - Effect of manipulations?
- Ultimate Goal
  - Middleware for monitoring and instrumenting complex topologies
  - Not necessarily only for PL networks
**Overlay Adaptation?**

- Separation of Measuring and Adaptation Phases
  - Notion of Times or Phases
- Large Overlay Networks in general …
  - Round-based Algorithms
  - State Machines
  - No reliable "Clocking" authority?
- Idea
  - Utilize Self-Synchronization Phenomena
A Self-Organized Notion of Time

**Epidemic Self-Synchronization**

Local Clocks ...
Kuramoto Oscillators

\[ \frac{d\theta_i}{dt} = \omega_i + K \cdot \sum_{j=1}^{N} \sin(\theta_j - \theta_i) \]

Kuramoto Oscillators

\[ \frac{d\theta_i}{dt} = \omega_i + K \cdot \sum_{j=1}^{N} \sin(\theta_j - \theta_i) \]
Couplings ...

- Problem with Kuramoto model
  - Coupling to all nodes
  - Continuously
    \[ \frac{\partial \theta_i}{\partial t} = \omega_i + K \cdot \sum_{j=1}^{N} \sin(\theta_j - \theta_i) \]

- A better idea
  - Coupling to single random neighbor
  - Periodically
  - Epidemic Synchronization

Geometric Random Graph
What about Dynamics?

- Exiting / Joining Peers?
- Perturbation

Effect on Synchronization?
- Can we somehow leverage stable hubs in Power Law Networks?
Results ...

(a) WS(1, 10), f_2, 0.1%
(b) BA, f_2, 0.1%
(c) BA, f_3, 0.1%
(d) WS(1, 10), f_2, 1%
(e) BA, f_2, 1%
(f) BA, f_3, 1%

Controllability ...

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Conclusion

- Three applications of Self-Organization
  - Flash Crowds
  - Adaptable P2P Overlay
  - Self-Organized and Robust Notion of Time

- What we can use …
  - Decentralized, efficient algorithms
  - Spontaneous emergence of order
  - Statistical / Thermodynamic Arguments
Further Reading


- [http://hyperverse.syssoft.uni-trier.de](http://hyperverse.syssoft.uni-trier.de)

Discussion Opener

„Distributed Systems are about to reach a *mesoscopic* scale. We will have to rely on thermodynamic principles to make them scalable, reliable and adaptive!“