The Physics of Algorithms

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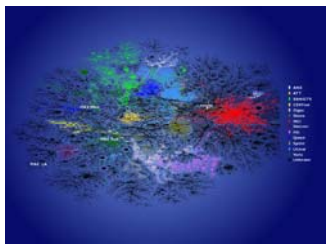
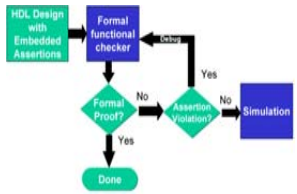
T-division: 3FTE, CCS-division: 2FTE, D-division: 0.25FTE



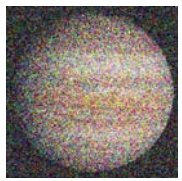
Internet router network

V & V

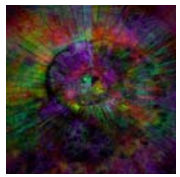


hardware & software

Image restoration



data storage



holographic, magneto-optic

Proposal:

Analyze existing and design new practical (i.e. computationally efficient!) algorithms for central challenges in Network and Computer sciences:

Algorithms in Network Science:

a) Community Detection (social networks) b) Routing, Coding and Optimization (e.g. sensor networks)

Algorithms in Computer Science:

a) Partitioning and Verification b) Data storage and retrieval c) Inference (image restoration)

Algorithms in support of LANL mission

Primary mission: Threat reduction (adversary networks, sensor networks)
Secondary missions: Weapons physics (high-performance computing, V&V)
Fundamental Science

LANL programs:

- National security: storage, coding, retrieval (CCS, T)
- Homeland security: sensor networks, BioWatch (CCS, D, T)
- V & V: software (formal) verification (CCS)
- Data analysis: image restoration (CCS, ISR,T)
- High performance computing: scheduling, partitioning (CCS, X, T)

Academia – intellectually deep (EU)

Industry – Microsoft, Google has interdisciplinary groups in area. Corning, Intel also work in this area.

LANL-larger simulations, lower tolerance for error. Specific effort is needed here!

Institutional tradition in physics of information:

- Metropolis Monte-Carlo
- Simulation Science, ASCI
- science archive xxx.lanl.gov
- genome project

LANL strategic investment in statistical physics: paying off with high-impact research, development of new programs, and cutting-edge basic science capabilities.

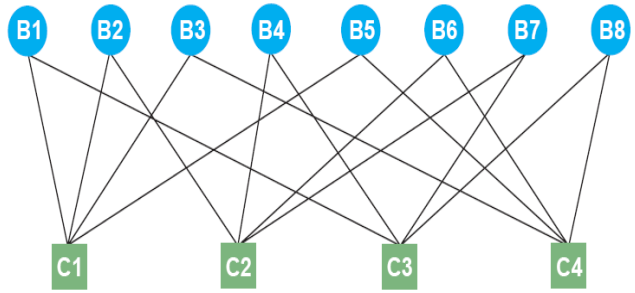
R & D approach

Efficient *Physics-based* Algorithms for emerging problems

Unifying theme: map information and computer science problems to physics systems

Physics methods:

- finite-size scaling, loop calculus
- phase transitions, universality
- stochastic calculus, optimal fluctuations
- renormalization-group
- percolation
- kinetic theory
- computational tree



Spin representation of decoding/computational device

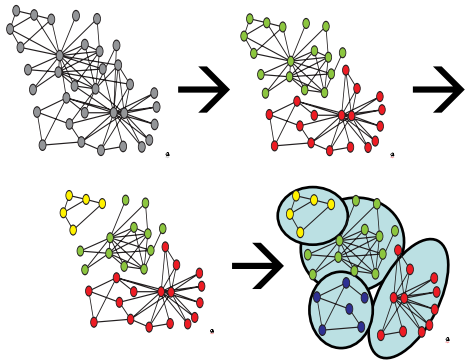
Our goals:

1) Develop efficient algorithms for computationally hard problems
2) Develop LANL application specific coding, routing and optimization algorithms
3) Analyze both typical and worst case scenarios
4) Analyze low probability events and design new algorithmic methodology

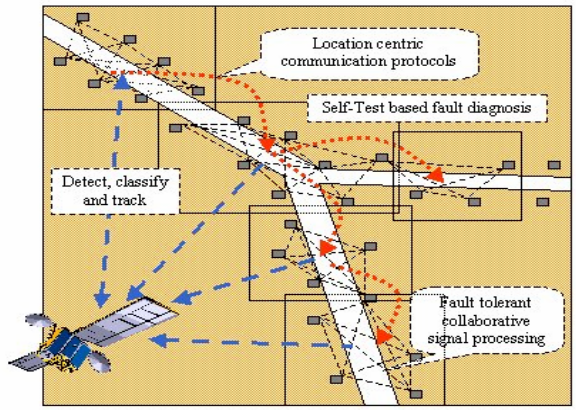
Pilot research in computer and information science:

- Statistical Physics of infrastructure networks (Ben-Naim PRE '04, Hastings PRL '04,'05)
- Retrieval Algorithms: nonlinear waves (Ben-Naim PRE '04, Hastings EPL '01)
- Coding: field theory and instanton (Chertkov & Stepanov PRL '04,'05)
- Rational improvement of belief propagation (Chertkov '06)
- Combinatorial Optimization: phase transitions (Percus, Istrate – Oxford Press '05)

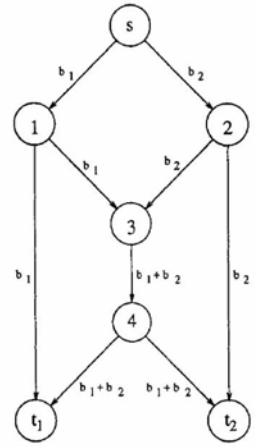
Proposed research in networks



Community detection,
Largest clique



Wireless Sensor Network -- complex real-world problem with algorithmic challenges in coding, routing and energy efficient clustering.



Network coding
(routing+coding)

Goals:

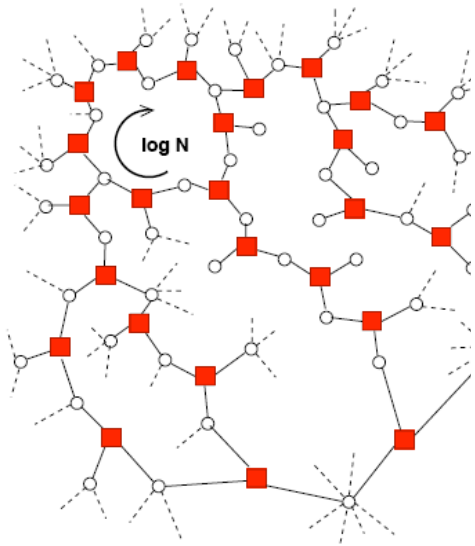
- Analyze performance of algorithms
- Provide improved algorithmic solutions

Methods:

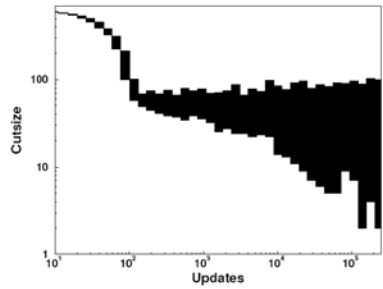
- Belief propagation, Survey propagation
- Loop-calculus
- Rare-event analysis

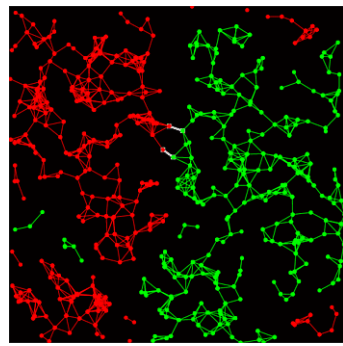
Deliverables:

- Provide LANL application-specific algorithms for network applications
- Computational toolbox for reliability estimation



Belief Propagation

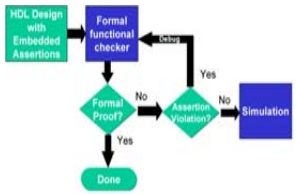




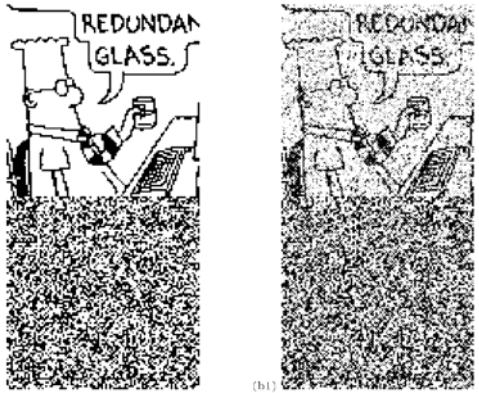
Extremal optimization

Proposed research in computer science

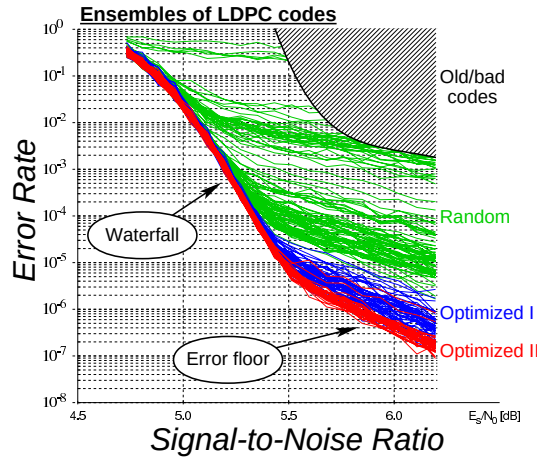
Rare event --- reliability analysis



Formal verification
for Hardware and Software
(example – "pentium" bug)



Data restoration (2d, 3d, coding)



Goals:

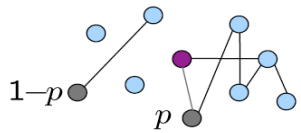
- Analyze and develop survey propagation and extremal optimization algorithms
- Analyze and develop storage, retrieval, ranking and data restoration algorithms

Methods:

- Phase transitions
- Extremal optimization
- Belief propagation, Survey propagation
- Kinetic theory
- Rare-event analysis
- Finite-size scaling

The page rank+search algorithms thm

- The random surfer model
  - With probability p follows a random **link**
  - With probability 1-p visits a random **site**



- Steady-state diffusion equation

$$P_i = (1-p) + p \sum_{j \to i} \frac{P_j}{N_j}$$

- PageRank(i)=$Ln_a P_i$

$$p = 0.85 \qquad a = 6$$

The anatomy of a Large-Scale hypertextual web search engine,
Serbey Brin and Lawrence Page

Google

Deliverables:

- V & V of ocean codes
- Efficient image restoration, storage, coding and ranking algorithm for LANL applications

Emphasize:

1) Finite system
2) Efficient algorithms
3) Critical applications

Institutional (LANL) impact

1. *New unique capabilities in*
   - stat phys & applied math
   - computer and information science
   - electrical engineering

2. *New science supporting existing programmatic efforts*

- Infrastructure and Communication Networks (new complex algorithms)
- Provide tools for V&V of LANL codes – finding a bug that a human cannot find + need different types of software compared to industry
- Image Restoration (2d,3d, trees – novel technology)
- Information processing and high-performance computing

3. *Program development*

- *Office of Science*
- *Department of Homeland Security*
- *Department of Defense*
- *DARPA*

Focus on mission critical applications