# The Internet is out of Breath or Is It?

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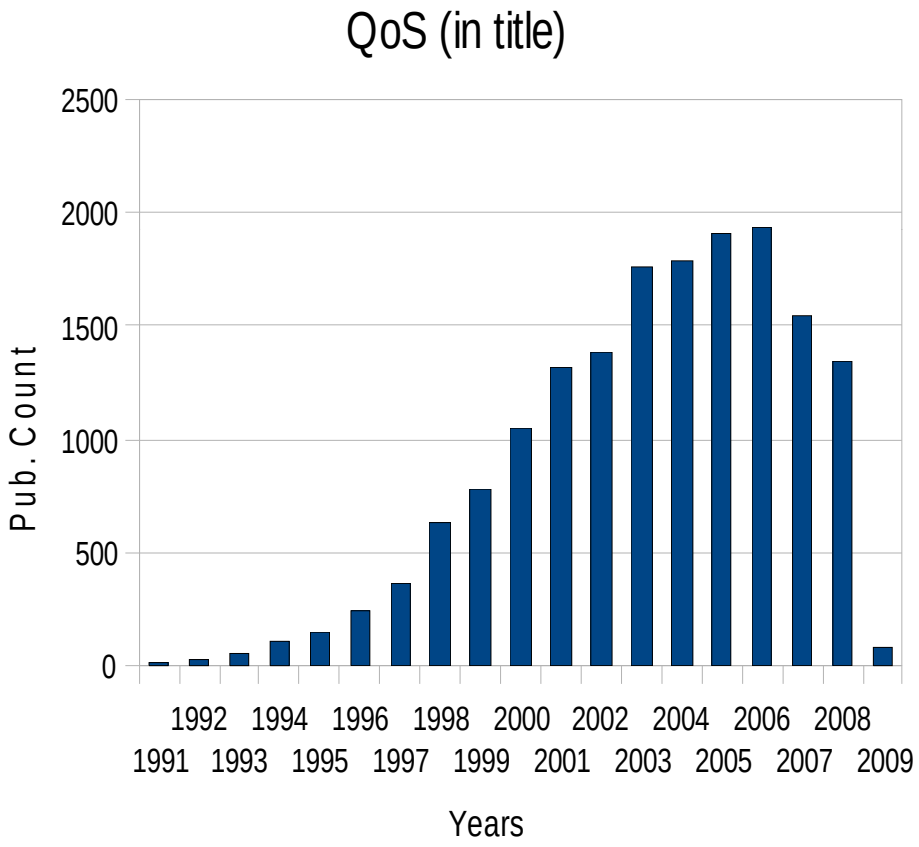
# What I'm Going to Try to Convey

The challenges of network innovation

1. You need to make sure you need it
   - The Internet is on its last leg
     - This is not the first time and probably not the last
   - What is today's Internet preventing us to do?
     - A still healthy growth curve by all accounts
2. Once you have it, you need to make sure users adopt it
   - We've had a new architecture for 15 years and it's barely starting to take-off
   - Do we really understand what drives network migration?
3. Once the network has been built, many of the important problems are in using it, not building a new one
   - This may be where the real (and interesting) problems are

# Internet Failure Predictions – (1)

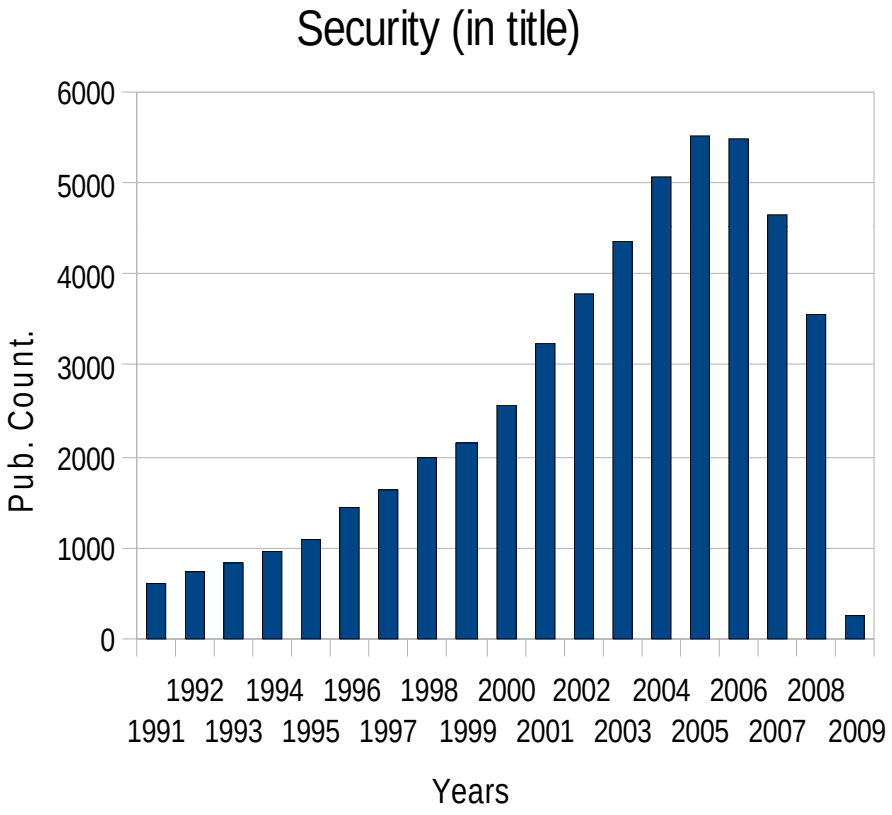
- Best effort can surely not be good enough!
  - The "race" for QoS
    - From Int-Serv, to Diff-Serv, to …
  - A phenomenal expenditure of intellectual resources
    - We've solved pretty much every QoS problem there was to solve
  - And… no one is really using the answers




From http://scholar.google.com/

# Internet Failure Predictions – (2)

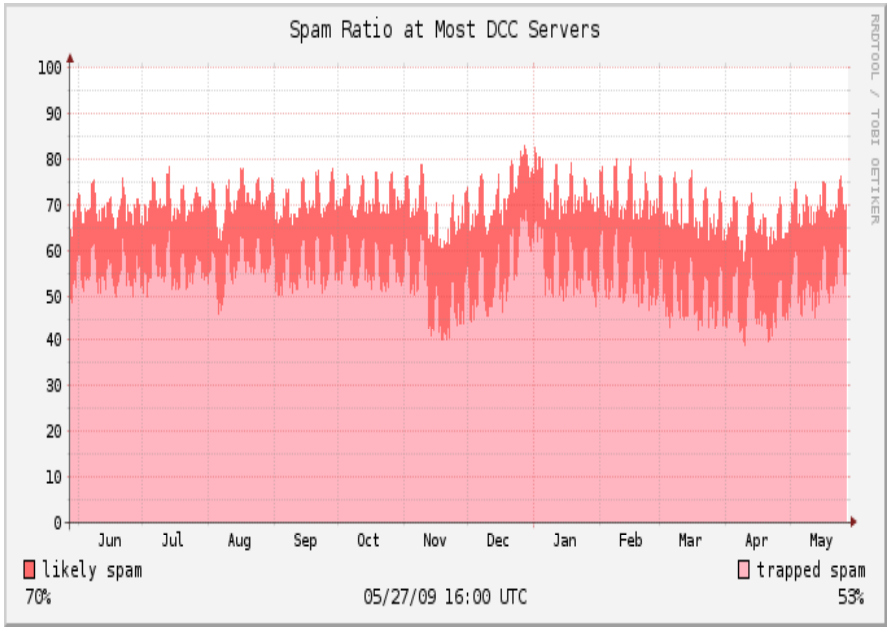
- An open network with distributed control can surely not be secure enough!
  - From BGP to S-BGP?
  - And lets not forget IPSEC, SPAM filters, honeypots, DDoS prevention, etc.
- It's not a perfect world, but things seem headed the "right" way



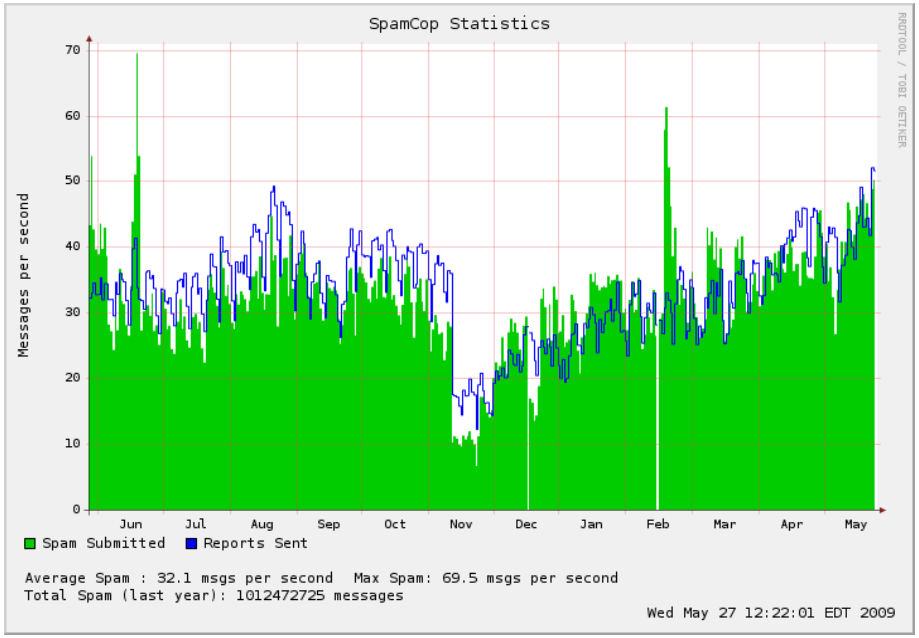

From [http://scholar.google.com/](http://scholar.google.com/)

# Spam – From Crisis to Boring Pain

This does not really look like exponential growth…



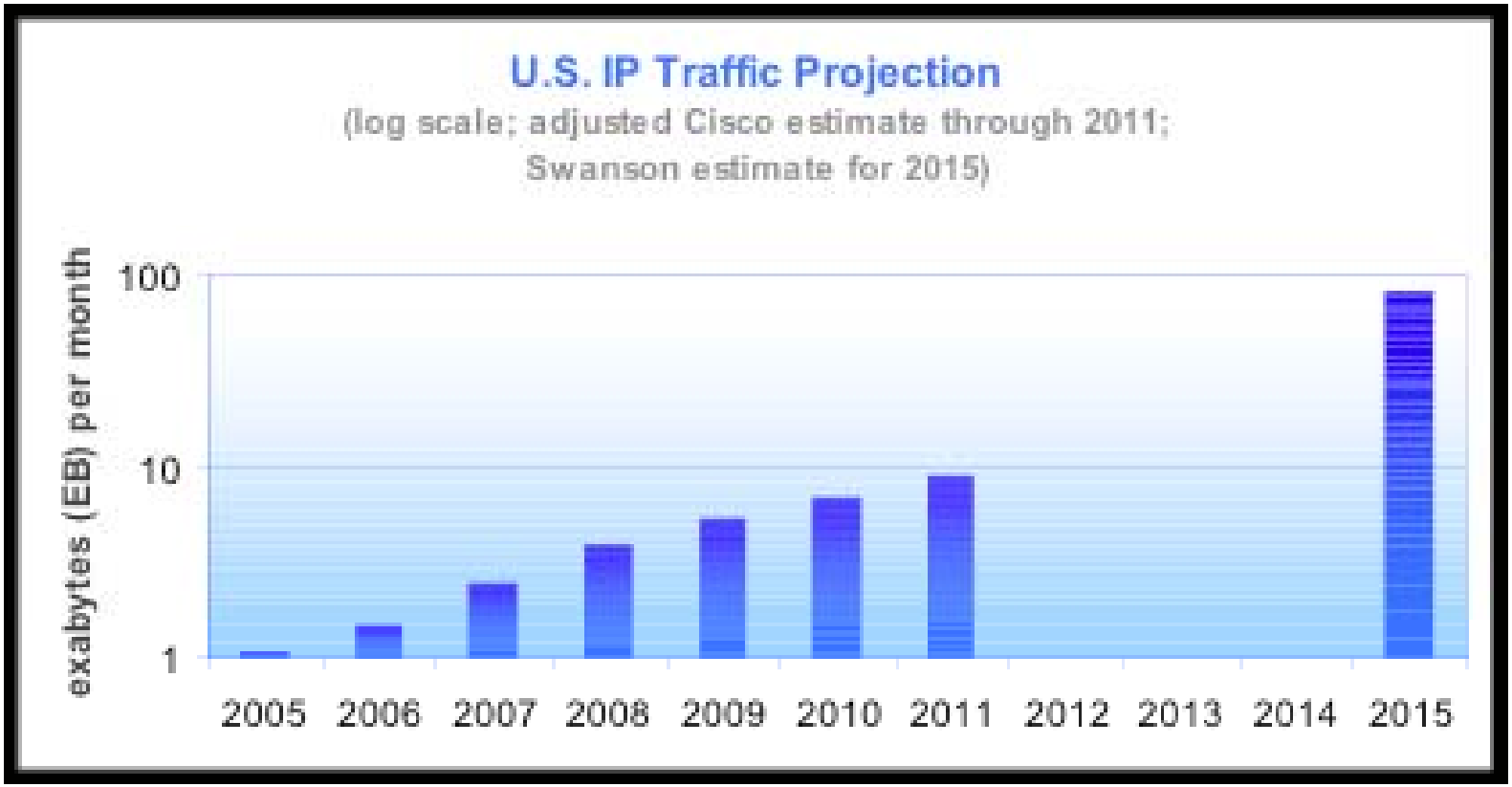

From http://www.dcc-servers.net/dcc/graphs/




From http://www.spamcop.net/spamstats.shtml

# On the Flip Side

Roughly a steady 50% annual growth rate for Internet traffic




From http://www.discovery.org/a/4428
See also http://www.dtc.umn.edu/mints/home.php for additional growth info

# More on Internet Traffic Growth

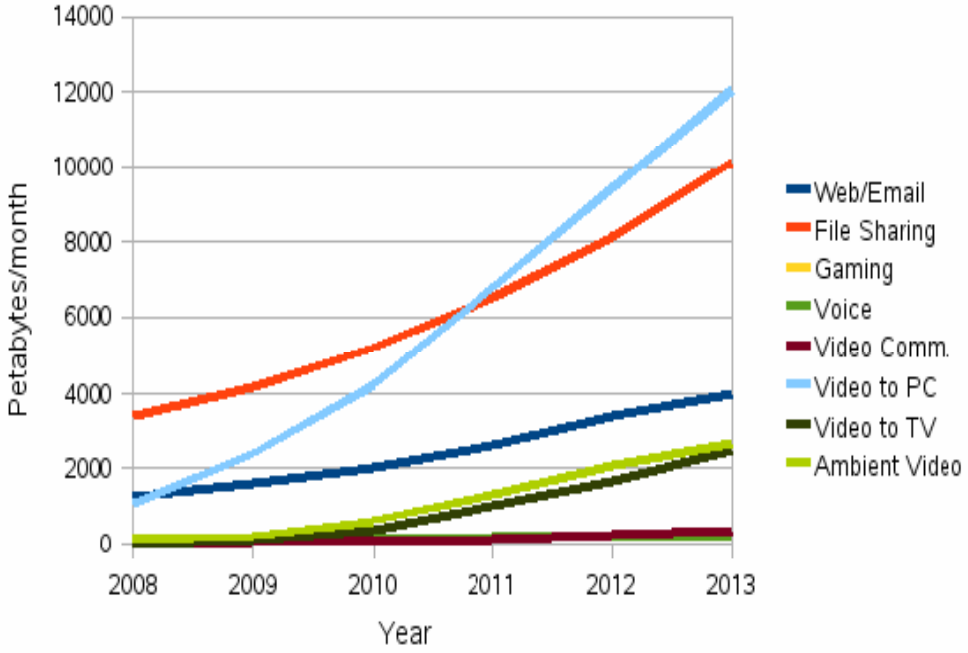
## The Past ~ 75-100+% AGR

From http://www.dtc.umn.edu/mints

| Year | AGR |
|---|---|
| 2003 | 75% |
| 2004 | 75% |
| 2005 | 115% |
| 2006 | 149% |
| 2007 | 58% |
| 2008 | 61% |

## The Future ~ 50% AGR

From Cisco Visual Networking Index




But, video is growing at ~100% AGR and expected to represent 90% of Internet traffic in 2013!

# Tracking Hulu

(http://www.yourbrandplan.com/forum/technology-innovation/11393-techcrunch-hulu-still-going-strong-but-growth-dropping-off-sharply.html)

| Month | comScore Video Metrix (000s) | | | | Nielsen VideoCensus (000s) | | | |
|---|---|---|---|---|---|---|---|---|
| | Ranking* | Overall Streams | Unique Viewers | Minutes Per Viewer | Ranking* | Overall Streams | Unique Viewers | Time Spent Viewing |
| Apr '08 | N/A | N/A | N/A | N/A | 10 | 63,228 | 2,428 | N/A |
| May '08 | 10 | 88,284 | 6,765 | 50.7 | 9 | 80,045 | 2,724 | N/A |
| Jun '08 | 9 | 95,093 | 8,277 | 47.7 | 10 | 83,838 | 2,611 | N/A |
| Jul '08 | 8 | 119,357 | 9,779 | 50.0 | 8 | 105,830 | 3,293 | N/A |
| Aug '08 | 9 | 122,124 | 10,201 | 52.6 | 8 | 107,622 | 2,632 | N/A |
| Sep '08 | 7 | 145,815 | 12,535 | 54.8 | 6 | 142,261 | 6,323 | 114.7 |
| Oct '08 | 6 | 235,096 | 23,993 | 113.8 | 3 | 206,068 | 9,069 | 119.2 |
| Nov '08 | 6 | 226,540 | 22,456 | 119.7 | 3 | 220,536 | 7,509 | 147.4 |
| Dec '08 | 6 | 240,585 | 24,572 | 99.0 | 4 | 216,344 | 6,679 | 177.8 |
| Jan '09 | 6 | 250,473 | 24,448 | 79.0 | 3 | 232,444 | 7,238 | 187.6 |
| Feb '09 | 4 | 332,504 | 34,731 | 64.5 | 2 | 308,806 | 9,473 | 176.9 |
| Mar '09 | 3 | 380,102 | 41,564 | 57.9 | 2 | 348,520 | 8,865 | 260.0 |
| Apr '09 | **3** | **396,953** | **40,110** | **61.0** | **2** | **373,290** | **7,458** | **324.9** |

# The Health of Internet Innovation (It's video but not just video)

| | # Videos (000) | # Viewers/mo (000) |
|---|---|---|
| Google sites | 6,367,638 | 101,870 |
| Fox Interactive | 551,991 | 62,109 |
| Yahoo! Sites | 374,161 | 41,859 |
| Viacom digital | 287,615 | 24,126 |
| Microsoft sites | 267,475 | 30,042 |
| Hulu | 250,473 | 24,448 |
| Turner Netw. | 195,983 | 22,979 |
| AOL | 184,808 | 27,198 |
| Disney Online | 141,452 | 13,435 |

| | Monthly users | Growth rates | Statistics |
|---|---|---|---|
| Facebook | 54.5M | 85% | 150M users |
| Twitter | 4.4M | 752% | >1B tweets |
| Linked-in | 11.9M | 153% | 30.1M users |
| YouTube | 71.3M | 21% | 258M users<br>100M videos/day |
| Flickr | 27.5M | 29% | >3B images |
| Digg | 33.4M | 91% | |
| Wikepedia | 59.6M | 15% | >10M articles |
| Blogs | 30M | 68% | 364M readers |

http://www.comscore.com/Press_Events/Press_Releases/2009/3/YouTube_Surpasses_100_Million_US_Viewers

http://www.quantcast.com/youtube.com
http://nmlab.com/download/1/

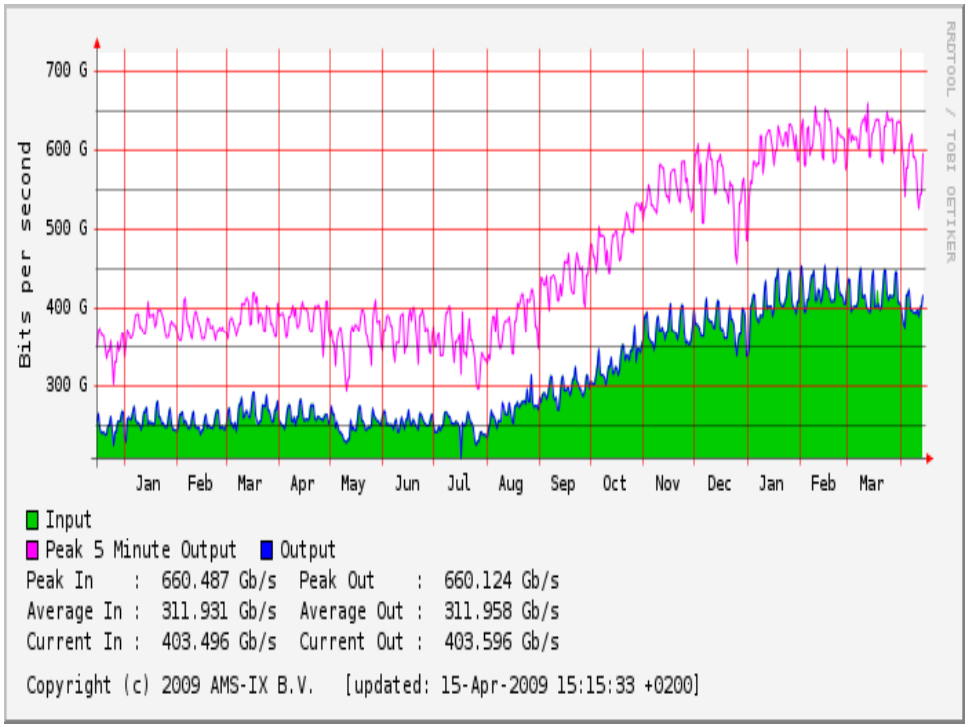
# Taking Stock

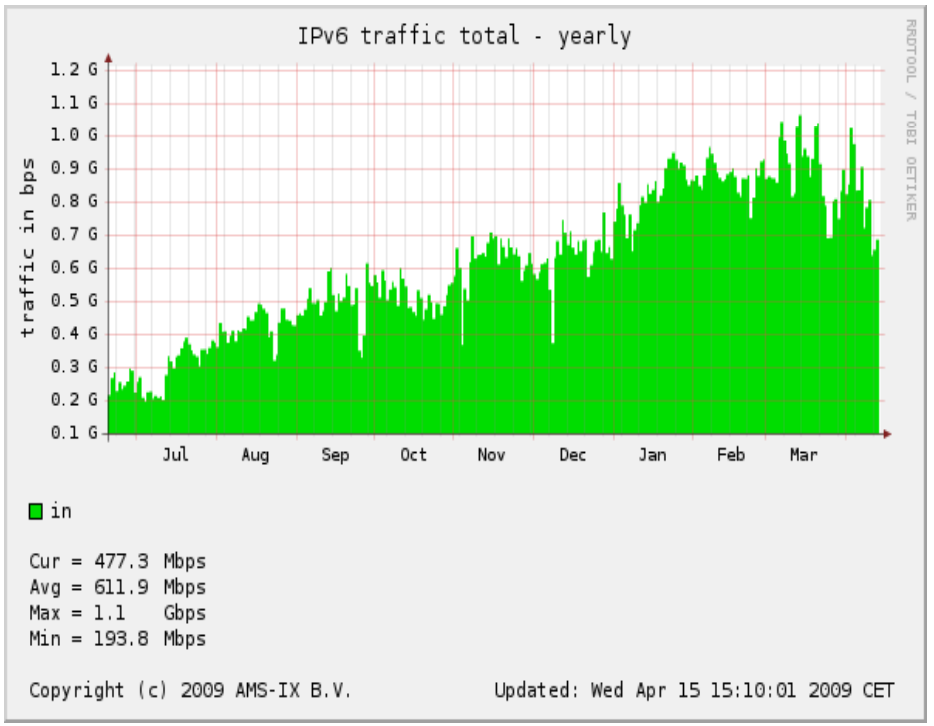
- There have been many past predictions of the Internet's demise
  - So far, they have been just that
- Today's Internet is still growing strong
  - About 50% AGR after over 20 years of ~100% AGR!
  - And some argue that video will give it a new boost
- It does not appear to be stifling innovation
  - A steady stream of new applications and uses
  - Solid growth across the board for existing apps and uses

# We May Still Need a New Network
## (some day)

- But, we've have had a new network for 15 years
  - It's called IPv6
  - It fixes a number of things with IPv4, though not everything
- But being better is not enough
  - Especially when dealing with a large incumbent
- We are starting to see some changes
  - Motivated by the emergence of a ***real*** problem and limitation of IPv4
  - But even now it's not obvious if/when IPv6 will really emerge

# IPv4 & IPv6 Yearly AMS-IX Traffic



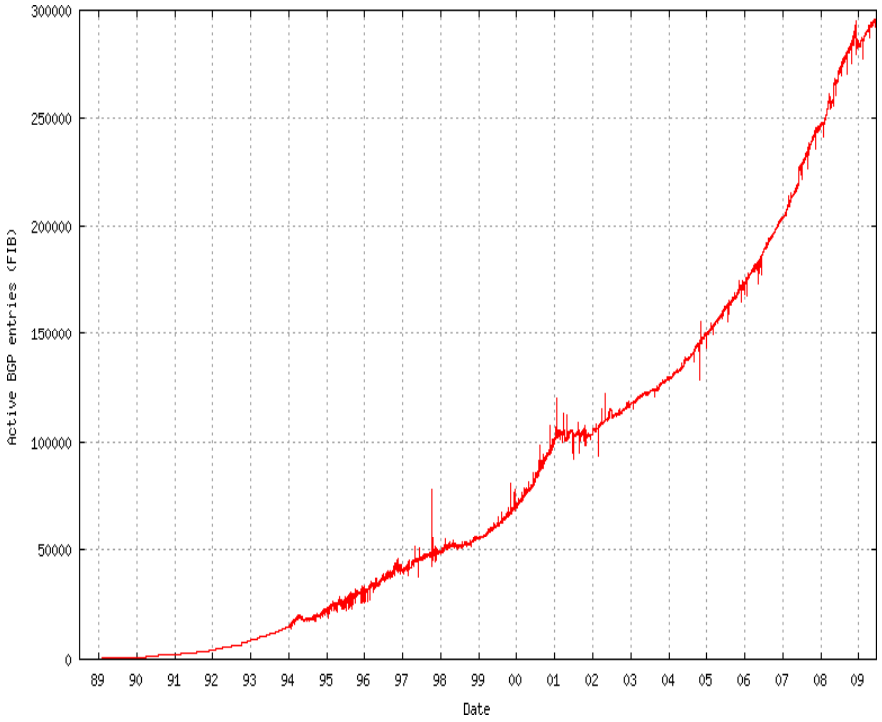




- After ~15 years since being standardized, IPv6 traffic amounts to about 0.2% of IPv4 traffic…

Source: AMS-IX web site - http://www.ams-ix.net/

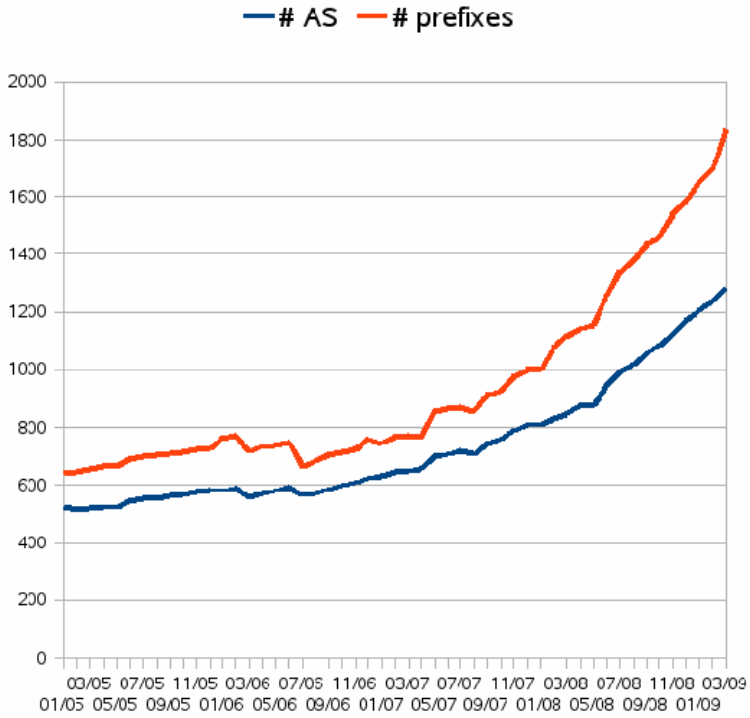
# Another Look at IPv4 & IPv6 Growth (routing)

IPv4




http://bgp.potaroo.net

IPv6




http://www.ipv6actnow.org/info/statistics/

# The Challenges of Network Migration

- Lets assume that some time in the distant future
  - We have created a much better network architecture that allows us to do things we simply cannot do on today's Internet
- The Internet will be pretty big by then
- What will it take for the new network to successfully displace the current Internet technology?

# An Attempt at a Simple Model*

- Two competing and incompatible networks, e.g., IPv4 and IPv6
  - Different qualities and price
  - Different installed base, e.g., one is starting from scratch
- Users individually (dis)adopt whichever technology gives them the highest positive ***utility***
  - Depends on technology intrinsic ***value*** and ***price***
  - Depends also on the number of users of each technology (***externality***)
- Gateways can offer a migration path
  - Overcome chicken-and-egg problem of first users
  - Effectiveness depends on gateways characteristics/performance
    - Duplex vs. simplex (independent in each direction or coupled)
    - Asymmetric vs. symmetric (performance/functionality wise)
    - Constrained vs. unconstrained (performance/functionality wise)

* http://repository.upenn.edu/ese_papers/496

# A Basic User Model

Technology 1: $U_1(\theta, x_1, x_2) = \theta q_1 + (x_1 + \alpha_1 \beta x_2) - p_1$

Technology 2: $U_2(\theta, x_1, x_2) = \theta q_2 + (\beta x_2 + \alpha_2 x_1) - p_2$

- Users evaluate the relative benefits of each technology
  - Intrinsic value of the technology ($\theta q_i$)
    - Tech. 2 better than tech. 1 ($q_2 > q_1$)
    - $\theta$ denotes user valuation of technology (captures heterogeneity)
  - Externalities: linear in # users ($0 \le x_1 + x_2 \le 1$) – Metcalfe's law
    - Possibly different across technologies ($\beta \neq 1$)
    - $\alpha_i$, $0 \le \alpha_i \le 1$, $i = 1,2$, captures gateways' performance
  - Cost (recurrent) for each technology ($p_i$)

# How Do Users Decide?

- Decision based on *indifference points*/*thresholds* for each technology: $\theta_1^0(\underline{x}),\ \theta_2^0(\underline{x}),\ \theta_2^1(\underline{x})$
  - $U_1(\theta, \underline{x}) > 0$ if $\theta \geq \theta_1^0(\underline{x})$ - Tech. 1 becomes attractive
  - $U_2(\theta, \underline{x}) > 0$ if $\theta \geq \theta_2^0(\underline{x})$ - Tech. 2 becomes attractive
  - $U_2(\theta, \underline{x}) > U_1(\theta, \underline{x})$ if $\theta \geq \theta_2^1(x)$ - Tech. 2 over Tech. 1
- Users are "rational" and choose:
  - Neither technology if $U_1 < 0,\ U_2 < 0$
  - Technology 1 if $U_1 > 0,\ U_1 > U_2$
  - Technology 2 if $U_2 > 0,\ U_1 < U_2$
- Decisions change as $\underline{x}$ evolves
  - Can formulate a diffusion model to capture evolution of decisions
  - Solving the model identifies possible equilibria and trajectories

# Two Possible Examples

1. IPv4 $\leftrightarrow$ IPv6
   – Duplex, asymmetric, constrained gateways

2. Low def. video conf. $\leftrightarrow$ High def. video conf.
   – Simplex, asymmetric, unconstrained converters

# IPv4 (Tech. 1) $\leftrightarrow$ IPv6 (Tech. 2)

IPv4: $U_1(\theta, x_1, x_2) = \theta q_1 + (x_1 + \alpha_1 \beta x_2) - p_1$

IPv6: $U_2(\theta, x_1, x_2) = \theta q_2 + (\beta x_2 + \alpha_2 x_1) - p_2$

- IPv4 and IPv6 are similar as "technologies" ($q_1 \approx q_2$ and $\beta = 1$)
- As IPv4 addresses become scarce
  - Providers start assigning IPv6 addresses to new subscribers ($p_{\text{IPv4}} = p_1 > p_2 = p_{\text{IPv6}}$)
- IPv6<->IPv4 gateways for transition to happen
  - Most content is ***not*** yet available on IPv6
    - Little in way of incentives for content providers to do it
  - Duplex, asymmetric, constrained converters
- Users choose technology primarily as a function of
  - Price ($p_{\text{IPv4}}$ vs. $p_{\text{IPv6}}$) and accessible content ($x_1$ vs. $x_2$)

# Low-def. video ↔ High-def. video

Low-def: $U_1(\theta, x_1, x_2) = \theta q_1 + (x_1 + \alpha_1 \beta x_2) - p_1$

High-def: $U_2(\theta, x_1, x_2) = \theta q_2 + (\beta x_2 + \alpha_2 x_1) - p_2$

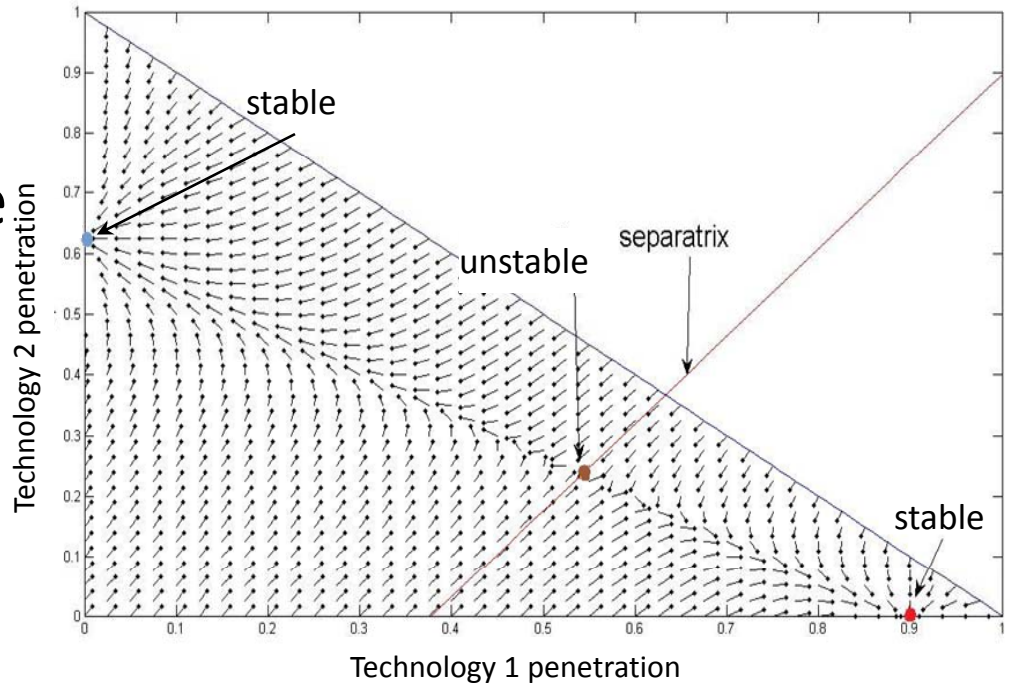
- Two video-conf service offerings: Low-def & High-def
  - Low-def has lower price ($p_1 < p_2$), but lower quality ($q_1 < q_2$)
  - Video is an *asymmetric* technology
    - Encoding is hard, decoding is easy
      - Low-def subscribers could ***display*** high-def signals but not generate them
    - Externality benefits of High-def are higher than those of Low-def ($\beta > 1$)
- Converters characteristics
  - High/Low-def user can decode Low/High-def video signal
  - Simplex, asymmetric, unconstrained
- Users choose technology as a function of
  - Price vs. quality trade-off
  - The level of externality benefits they can enjoy

# What Do We Learn from the Model?

- What are possible outcomes?
  - Combinations of equilibria
- What trajectories to equilibria?
  - Monotonic vs. chaotic
- What roles for gateways?
  - Do they help and how much?

# A “Typical” Outcome

- At most two stable equilibria
- Coexistence is possible
- Final outcome is hard to predict simply from observing the evolution of adoption decisions



# Applying the Model to IPv4→IPv6

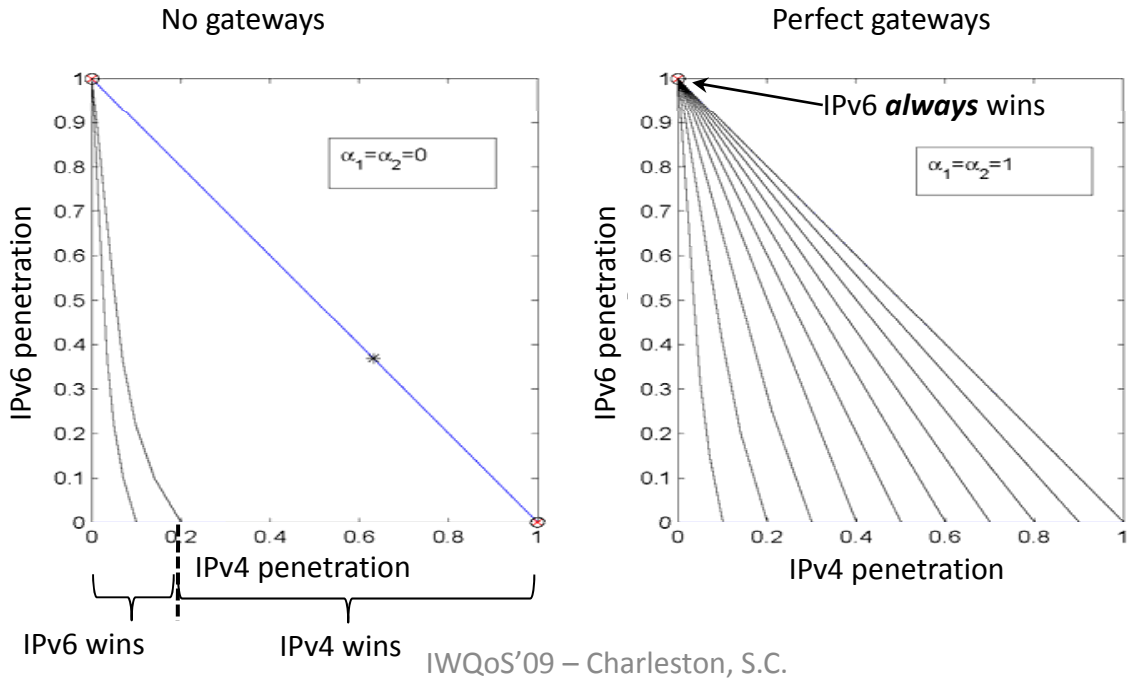
- Two possible scenarios (nothing surprising in either)

  1. IPv4 slightly "better" than IPv6
     - Greater user familiarity with technology
  2. IPv6 slightly "better" than IPv4
     - More addresses, better security and/or mobility

- Both yield similar behaviors and highlight the role of gateways

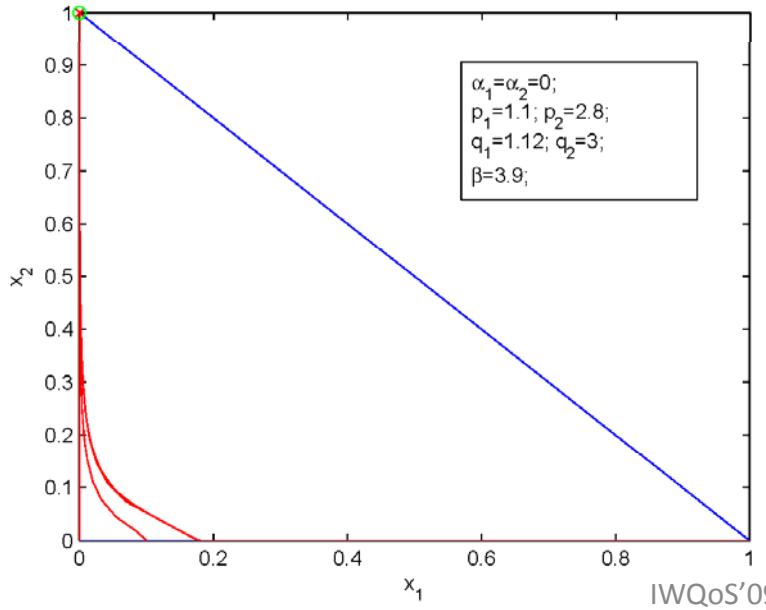
# IPv6 “Better” than IPv4

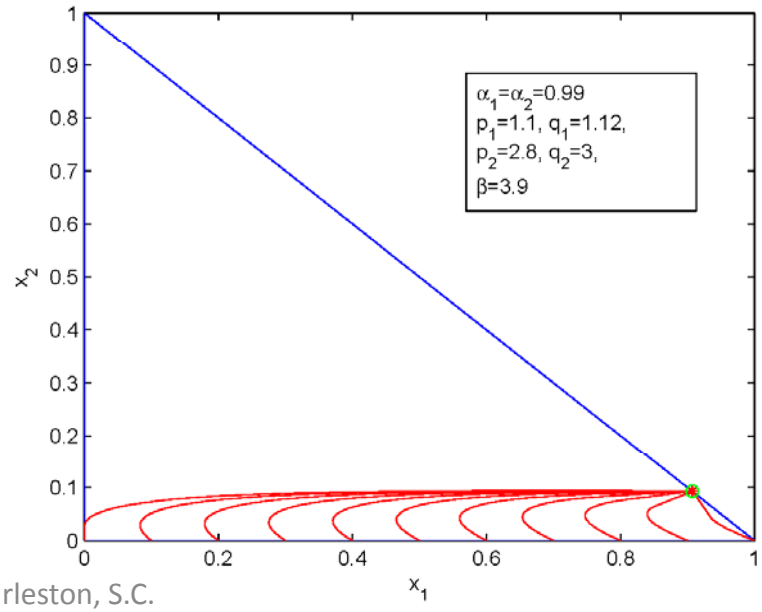
- Without gateways, IPv6 never takes off if it starts late
- With “perfect” gateways, IPv6 always eventually win
  - But gateways must be better than a minimum threshold
- This is an instance where gateways help defeat the incumbent



# Gateways Can Also Help the Incumbent

- No gateways: Tech. 2 wipes out Tech. 1
- Perfect gateways: Tech. 1 nearly wipes out Tech. 2



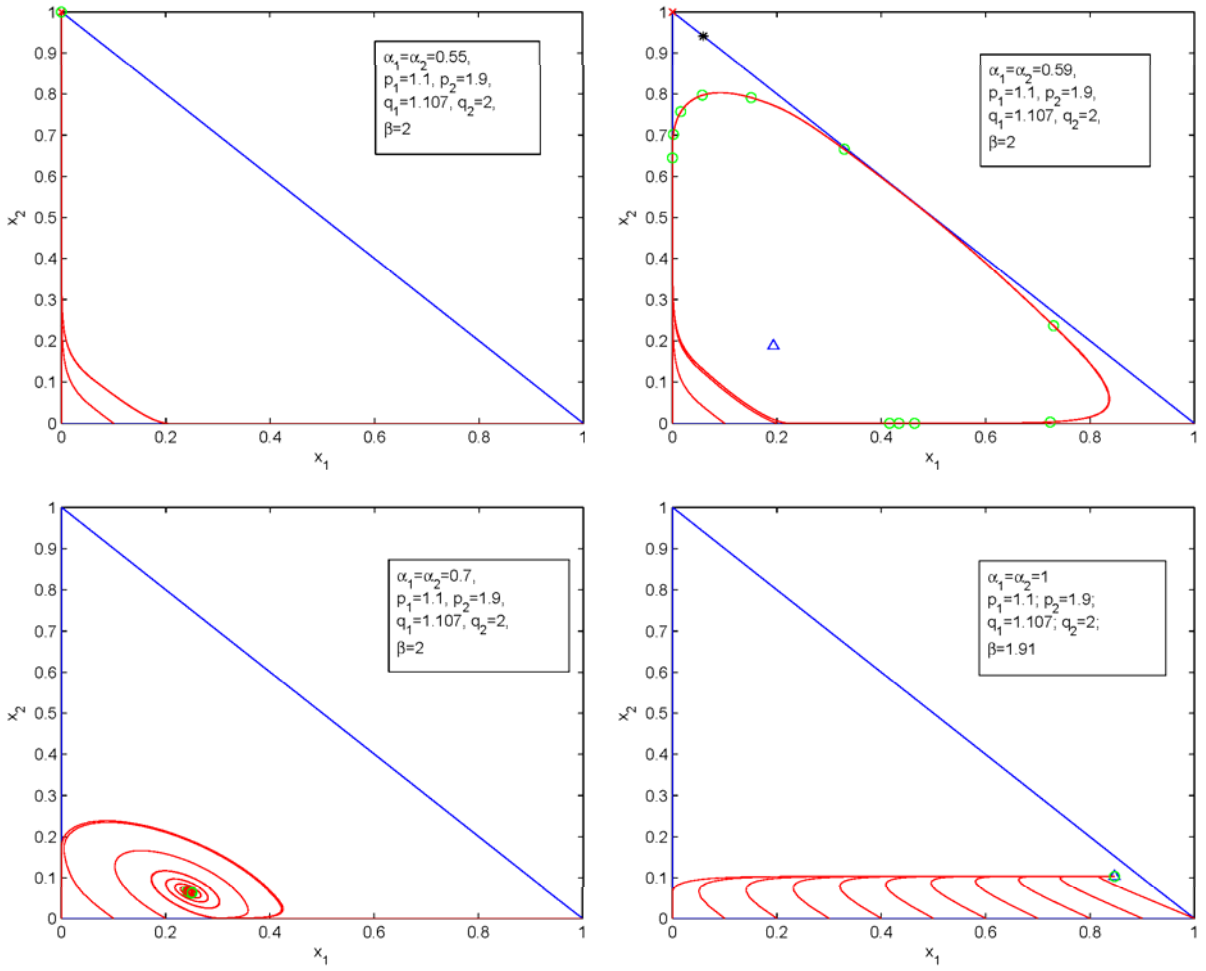



# More Bad Gateway Behaviors

- Better gateways can harm overall market penetration
- Gateways can also render the adoption process unstable
  - Perpetual cycles of adoption/disadoption
  - This only happens when the new technology is significantly better, and users of the incumbent can tap into those benefits through gateways (the video example)

# When Things Go Really Wrong

- No gateways: Tech. 2 captures full market
- Low efficiency gateways: No stable outcome
- Medium efficiency gateways: Pitiful overall market penetration
- High efficiency gateways: Tech. 1 dominates at close to full market penetration



# How Serious is This?

- Most/all results are actually robust to a wide range of modeling changes (not just a modeling artifact)
  - User preferences ($\theta$)
    - Arbitrary distributions
    - Extended to externality benefits
  - Externality effect
    - Sub-linear: $x^{\alpha}$, $0<\alpha<1$
    - Super-linear: $x^{\alpha}$, $\alpha>1$
    - Logarithmic: $\log(x+1)$

# The Net of It

Caution is in order when

- Deploying a new network technology with strong externality effects, an entrenched incumbent, and
- Deciding how good a gateway to build

***If you build it, they may not come…***

# If Building New Networks Is Dicey, What Else Can We Do?

- There are lots of interesting problems that arise when everything is ***networked***
- Broadly speaking, this is what people have recently been calling *NETWORK SCIENCE*

- It's an abused term that nevertheless spans some really interesting areas

# One Out Of Many Examples

- Consider a networked system, e.g., a social network à la Facebook
- We want to deploy a new application/feature
  - Its value to users depends on how many others are using it (another instance of externalities)

$$U_i(a_i, \mathcal{A}) = a_i \left[ \sum_{j \in \mathcal{A} \setminus \{i\}} w_{ij} a_j + w_{ii} - p \right]$$

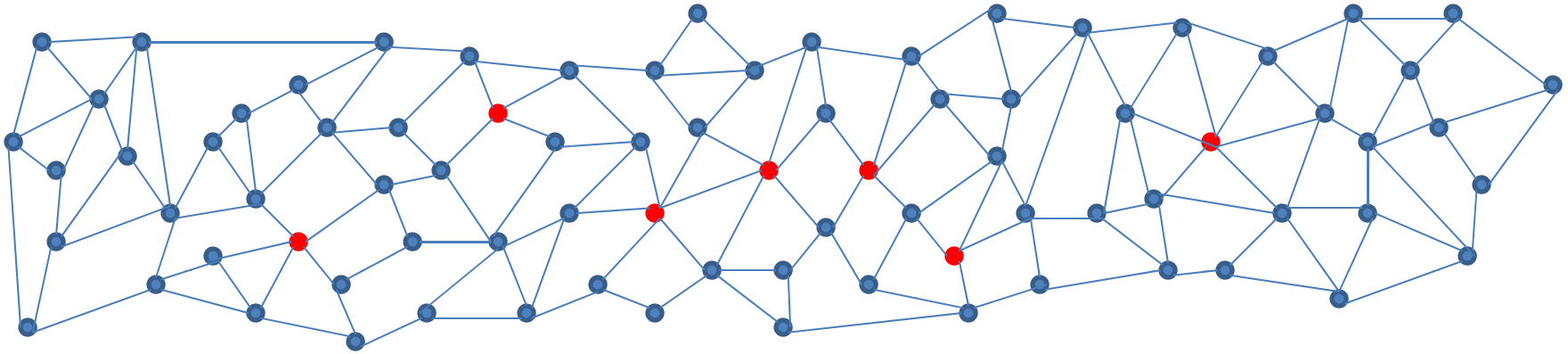
    - $a_i$: adoption decision, $\mathcal{A}$: set of adopters, $w_{ij}$: edge weight between $i$ and $j$, $w_{ii}$: intrinsic value, $p$: price
- Chicken and egg adoption decision

# Fostering Adoption

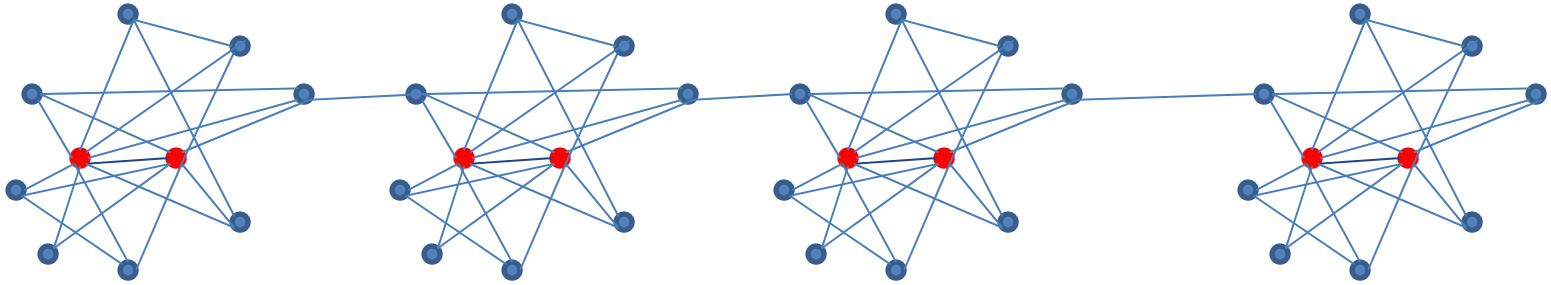
- A strategy based on *seeding*
  - Give technology away (free or cheap) to a small number of users to bootstrap the adoption process
- Basic question: Who should I give it to?
- Can be formulated as an optimization problem
  - Like many network optimization problems, it is NP-hard in most settings
  - Many "folks" heuristics have been used and proposed, e.g., the concept of influentials [1]

[1] D.J. Watts and P.S. Dodds, "Influentials, Networks, and Public Opinion Formation." Journal of Consumer Research, Dec. 2007.

# Network Structure and Seeding Strategy



Seeding one city or several villages?



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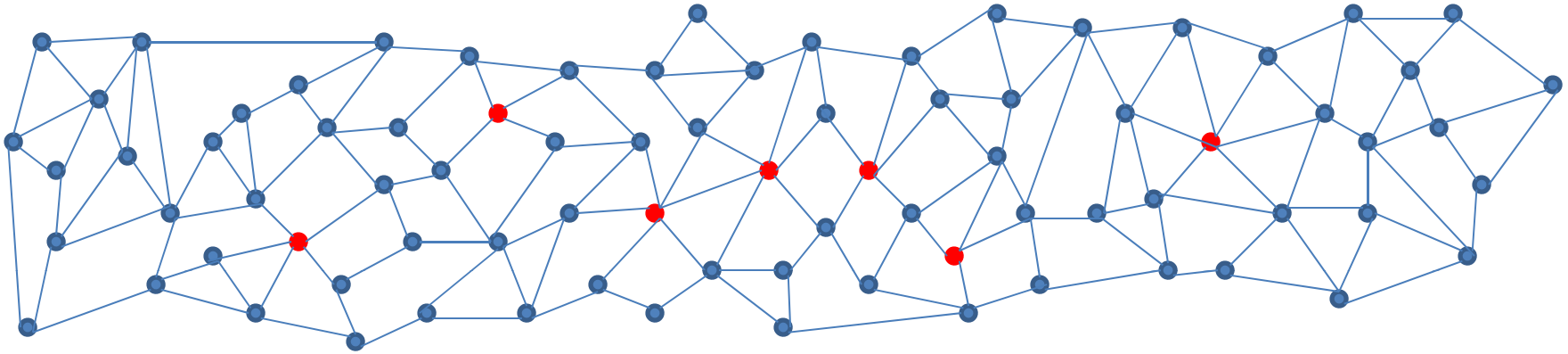

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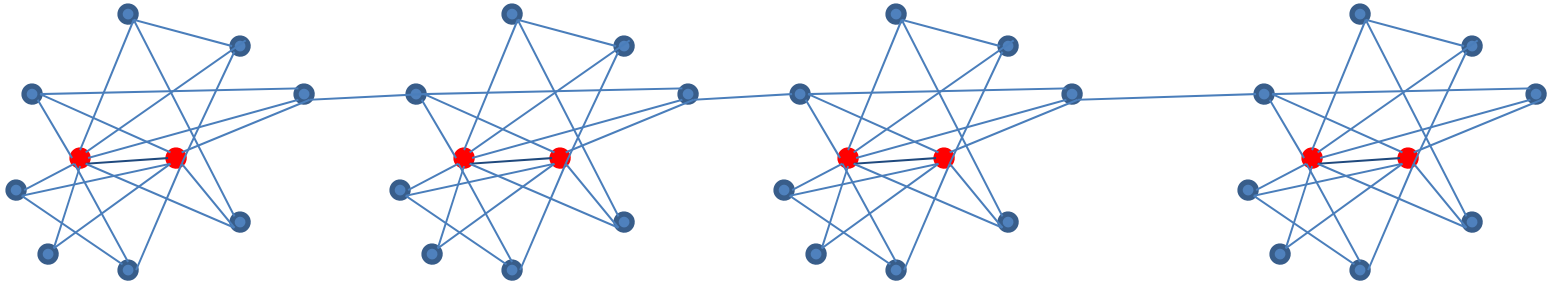

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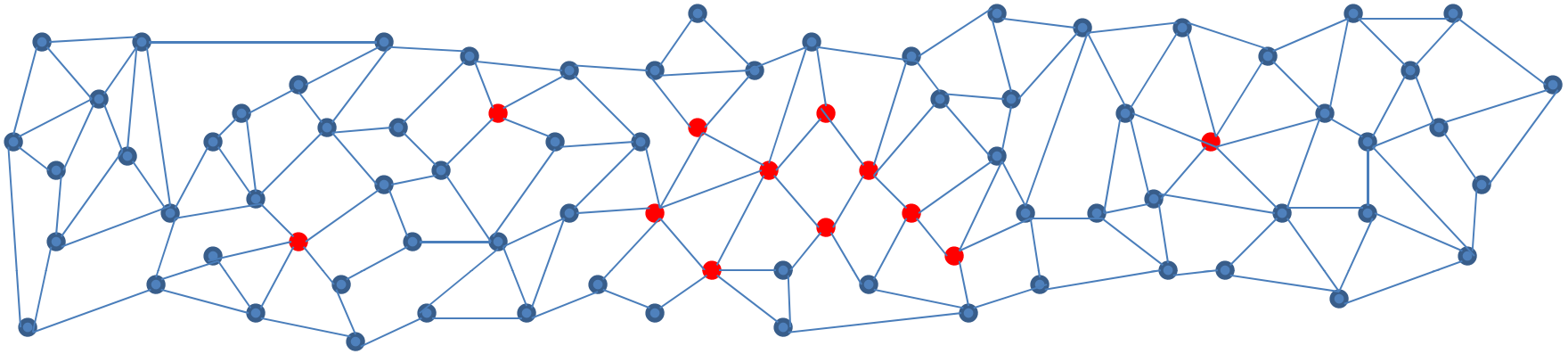

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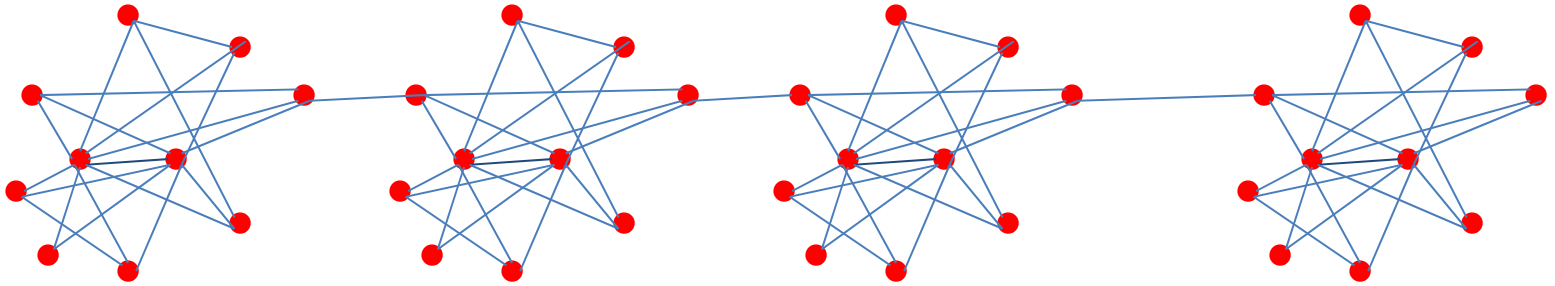

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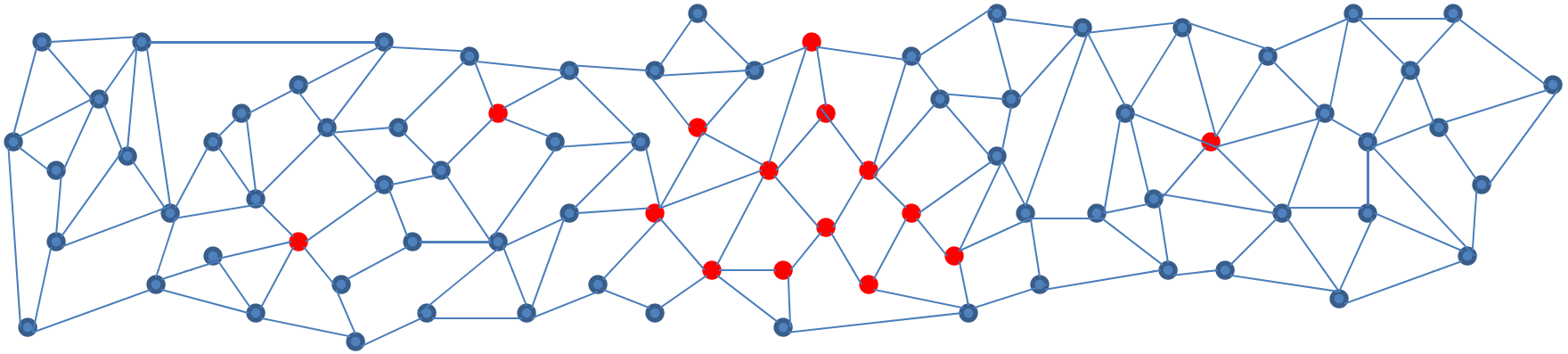

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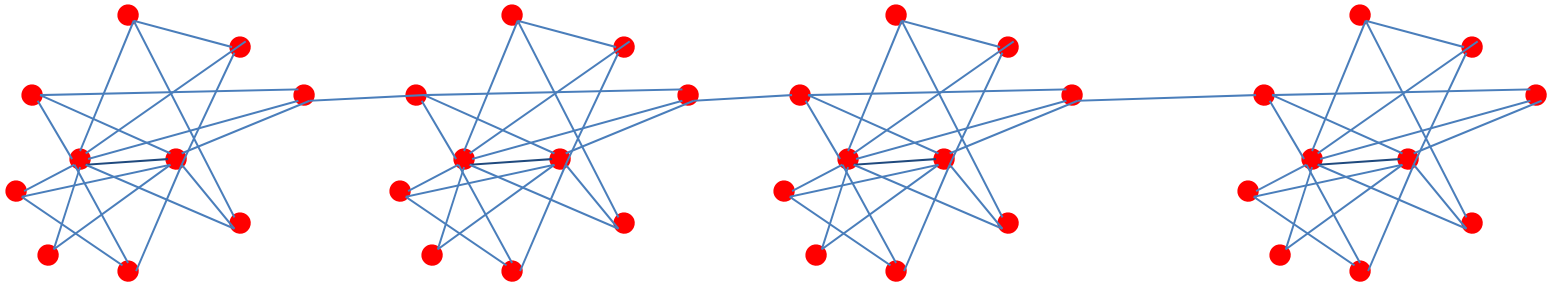

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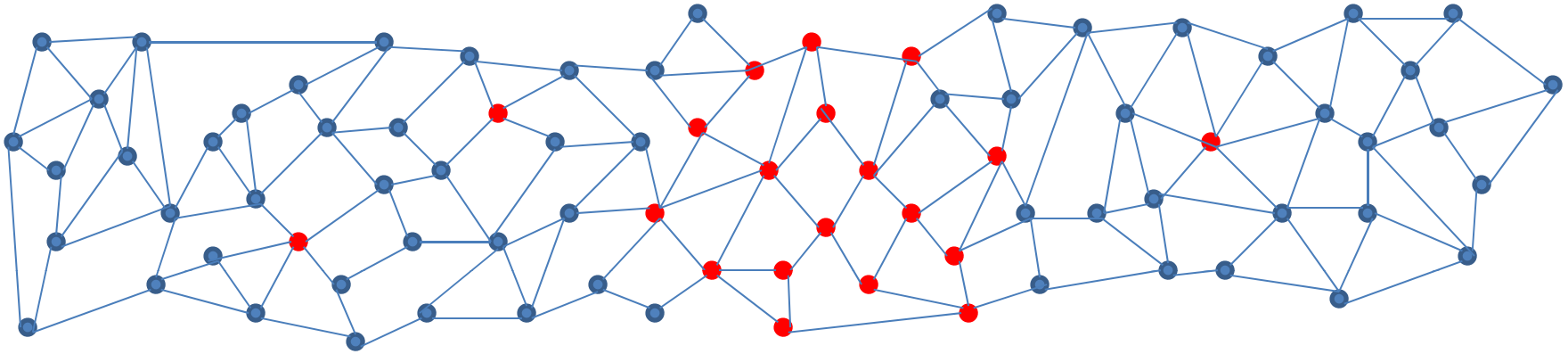

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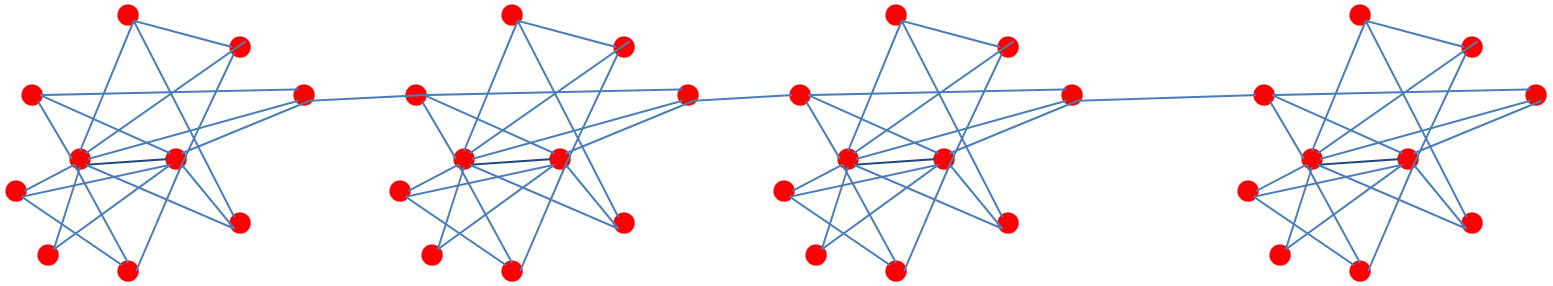

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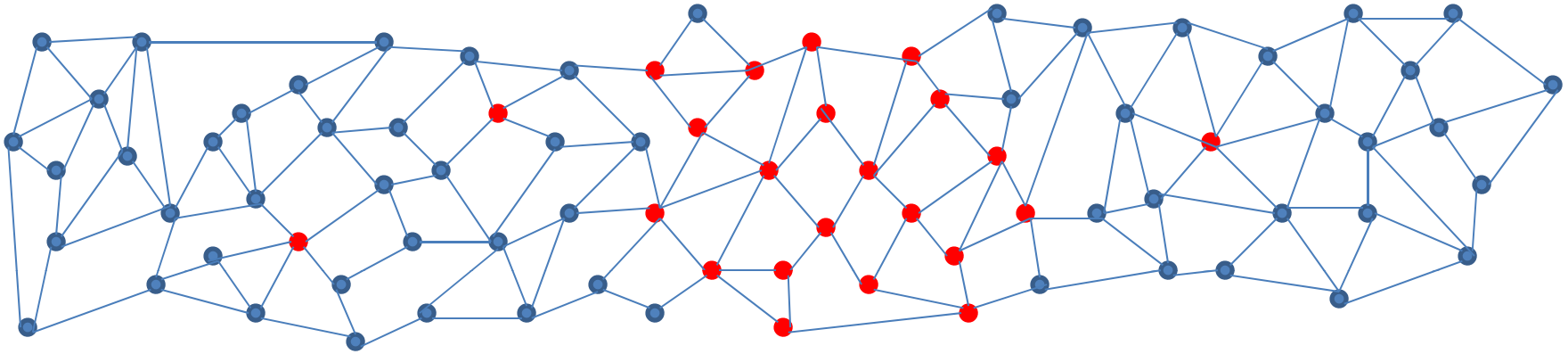

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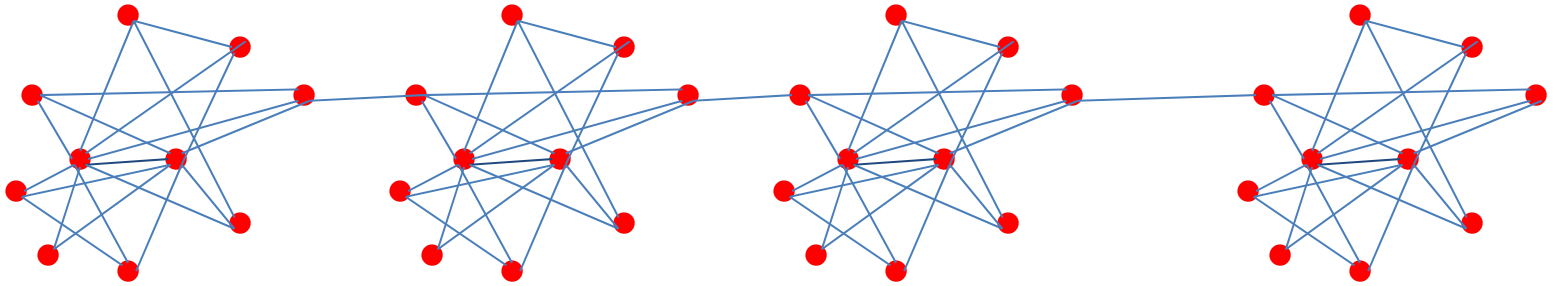

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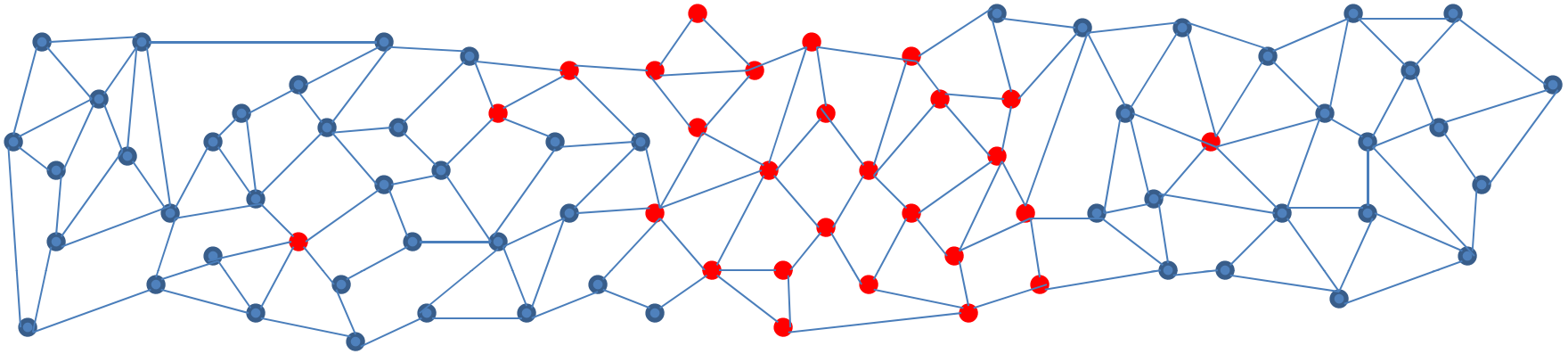

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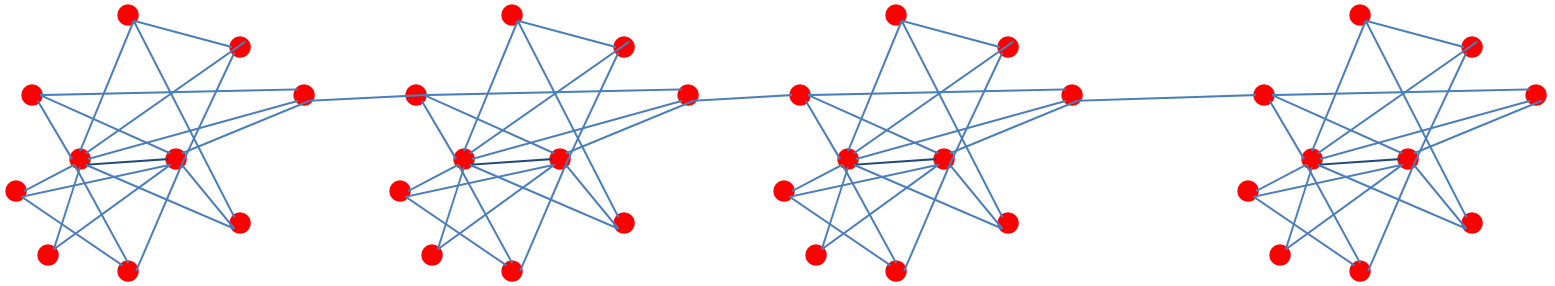

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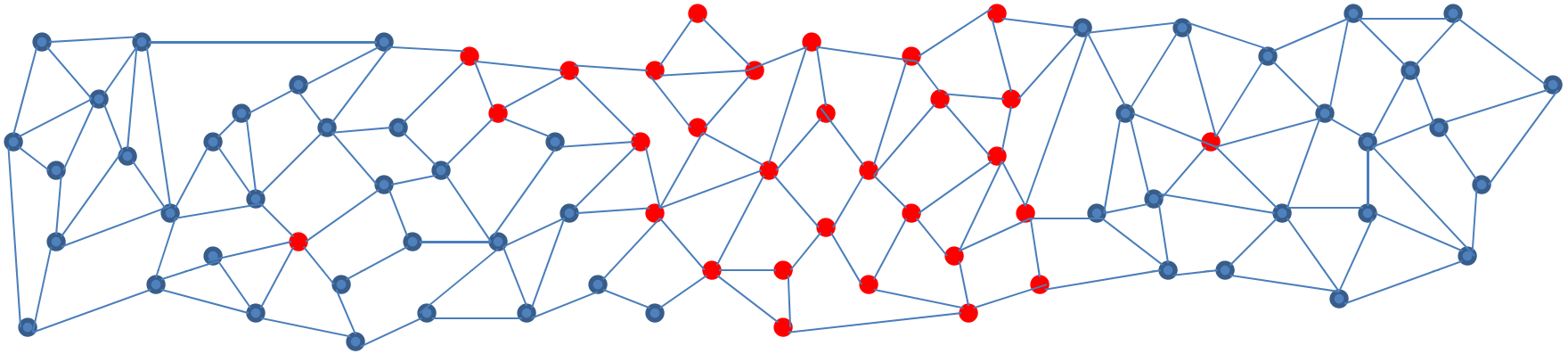

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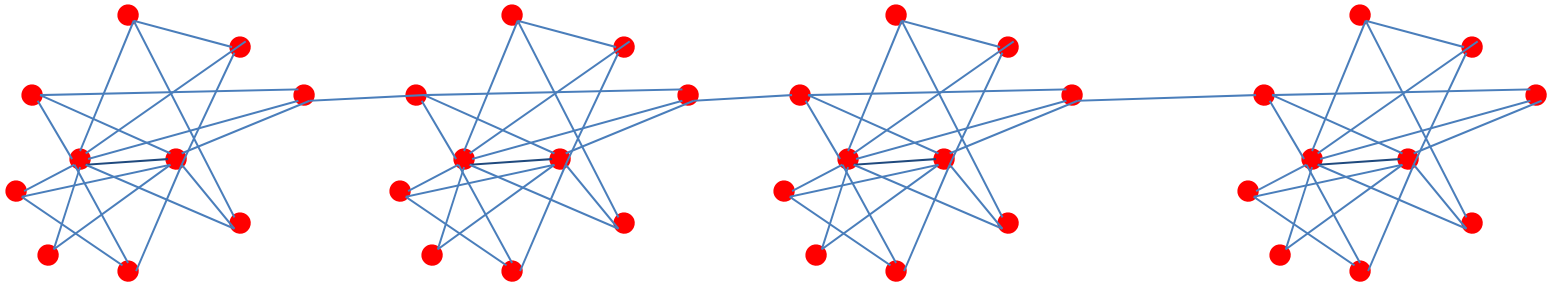

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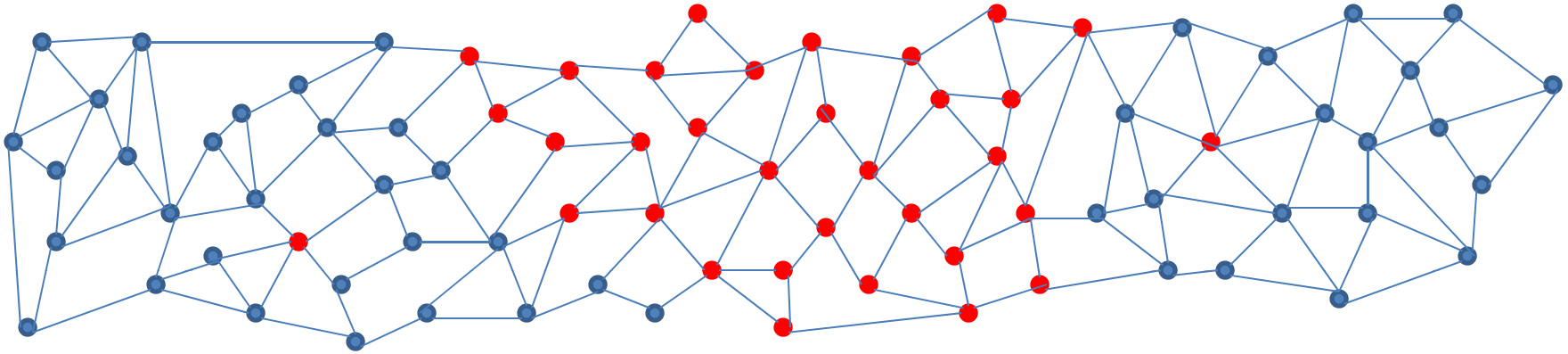

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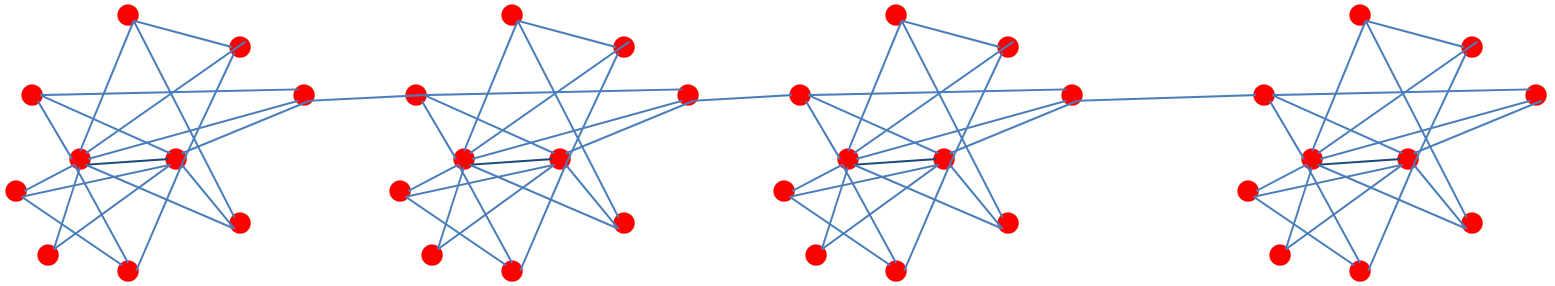

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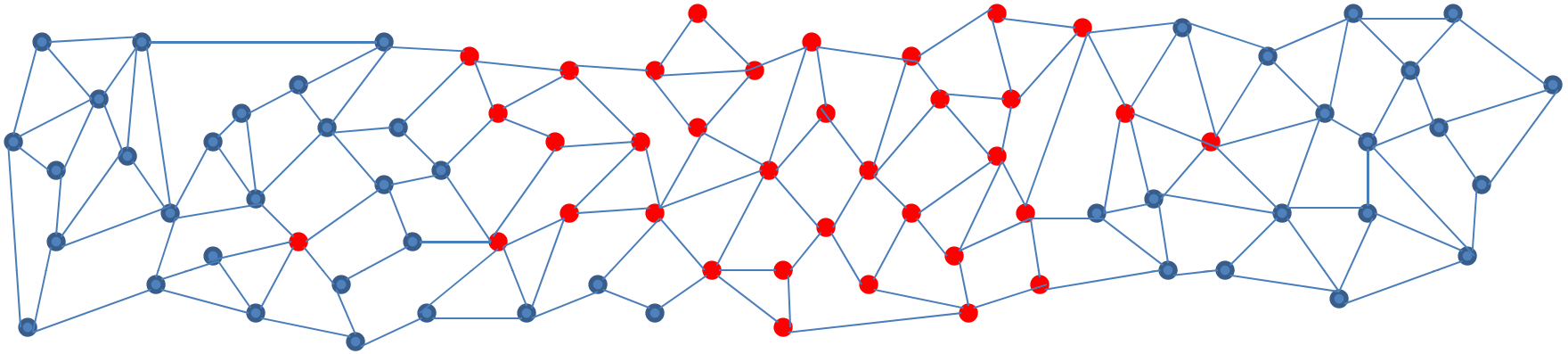

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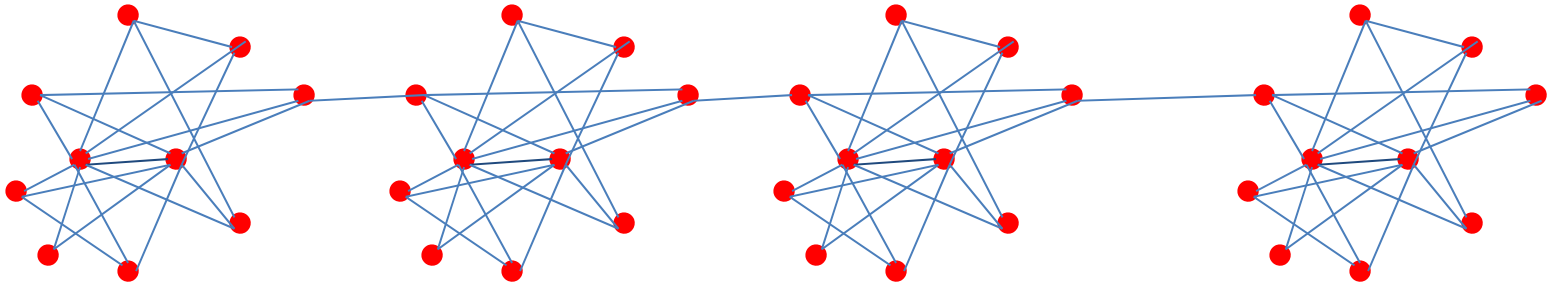

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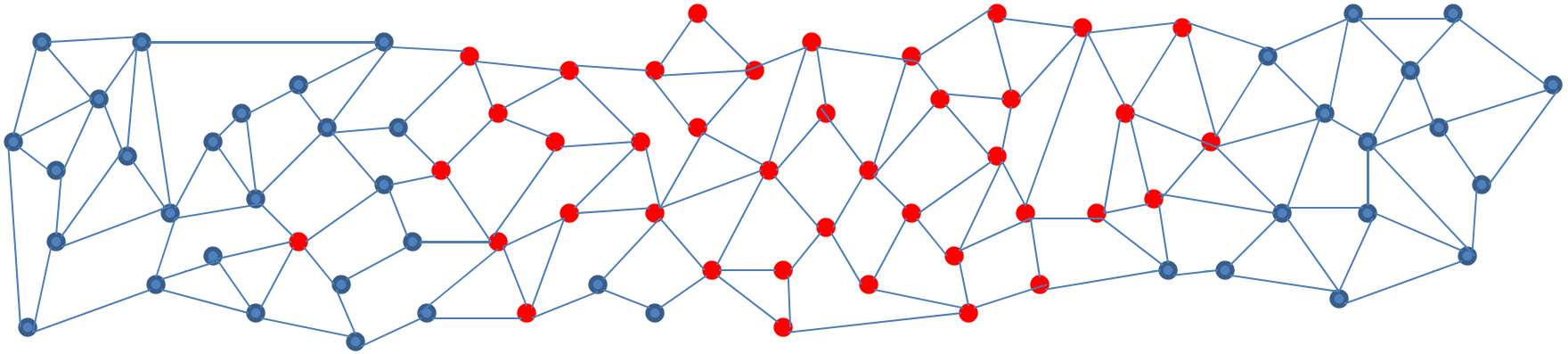

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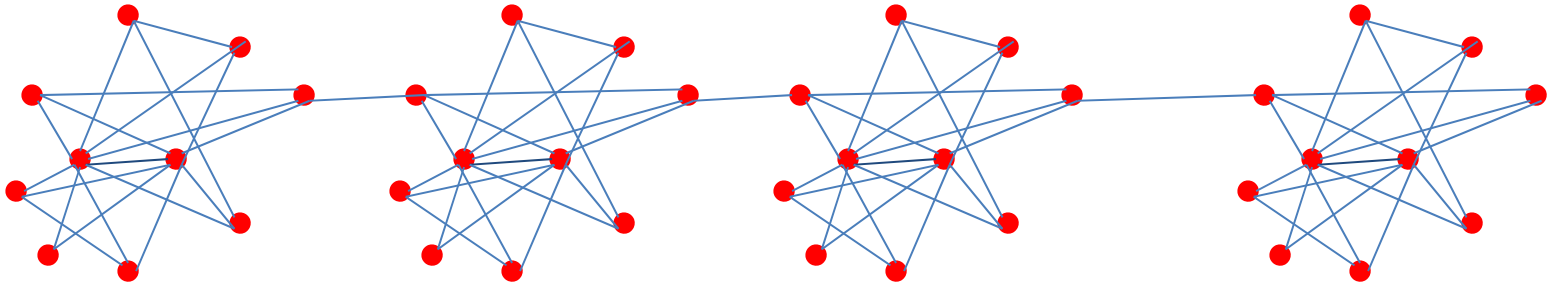

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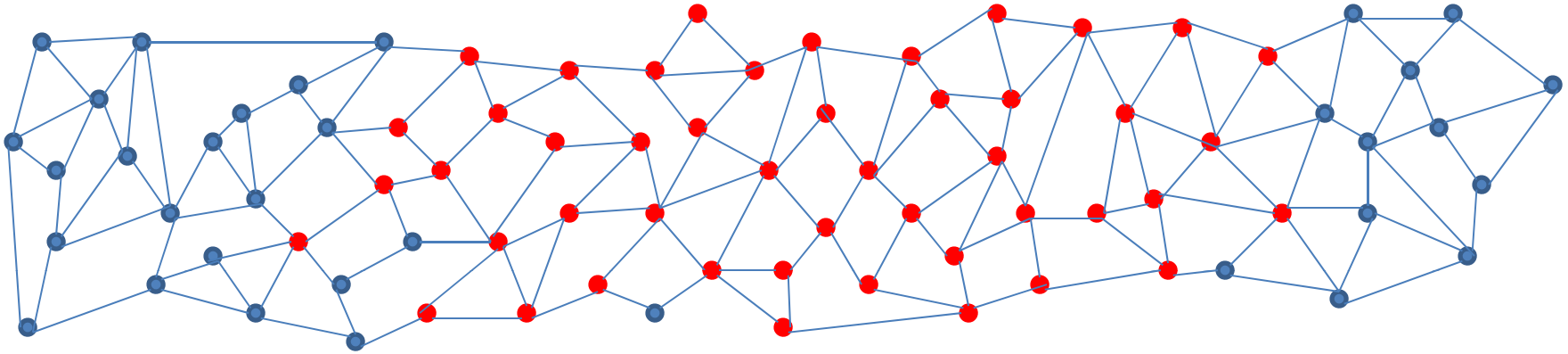

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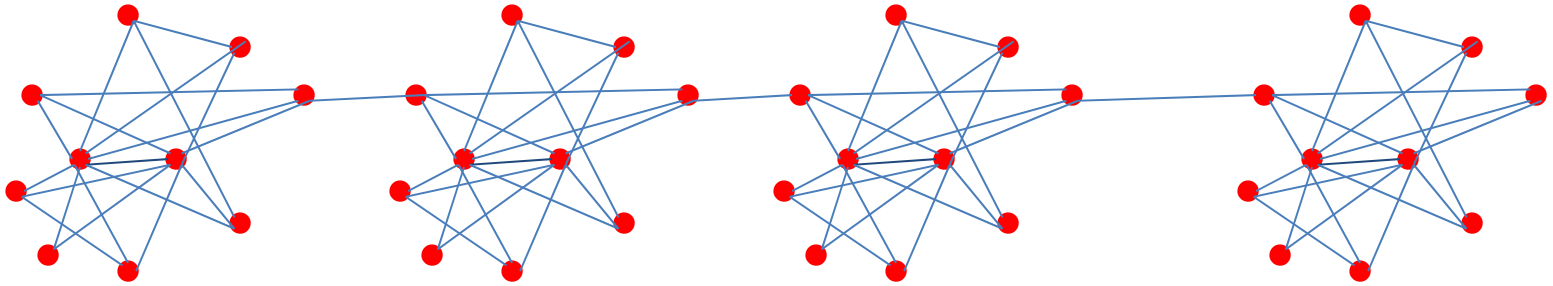

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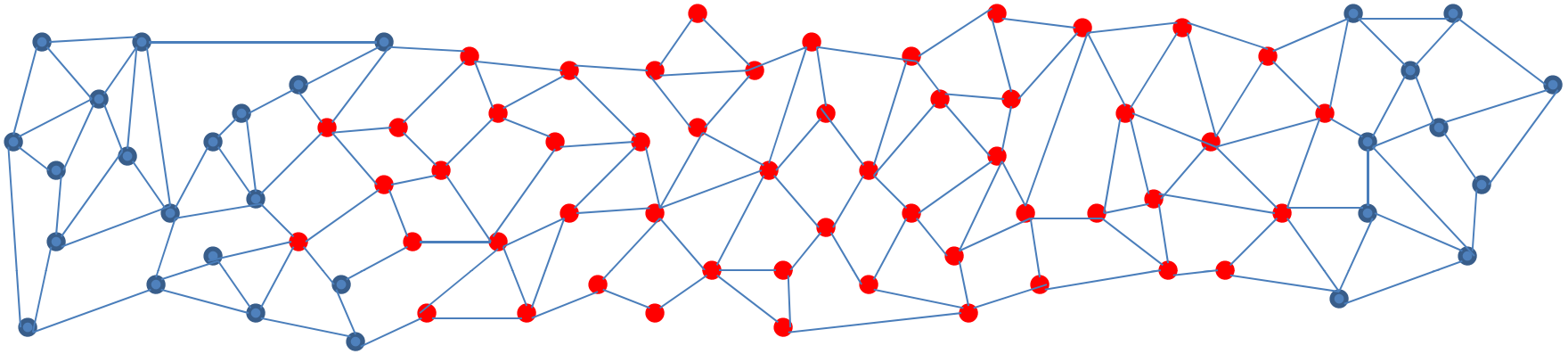

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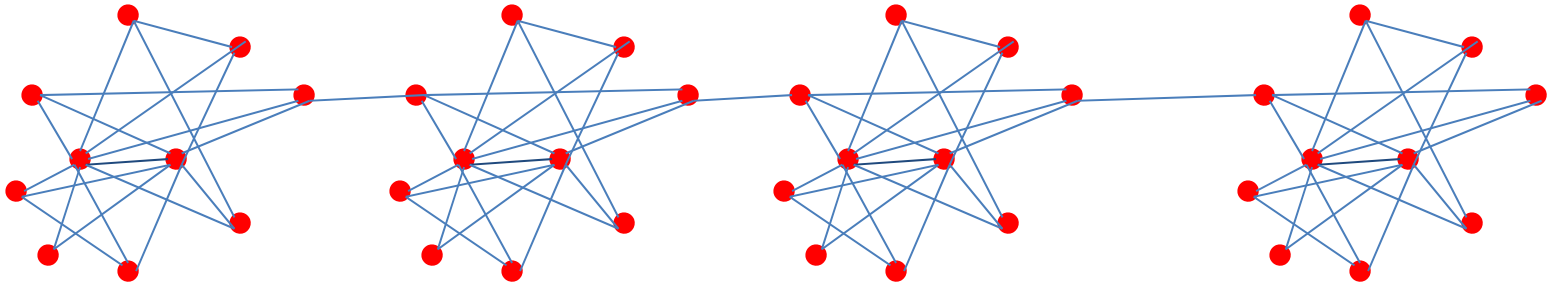

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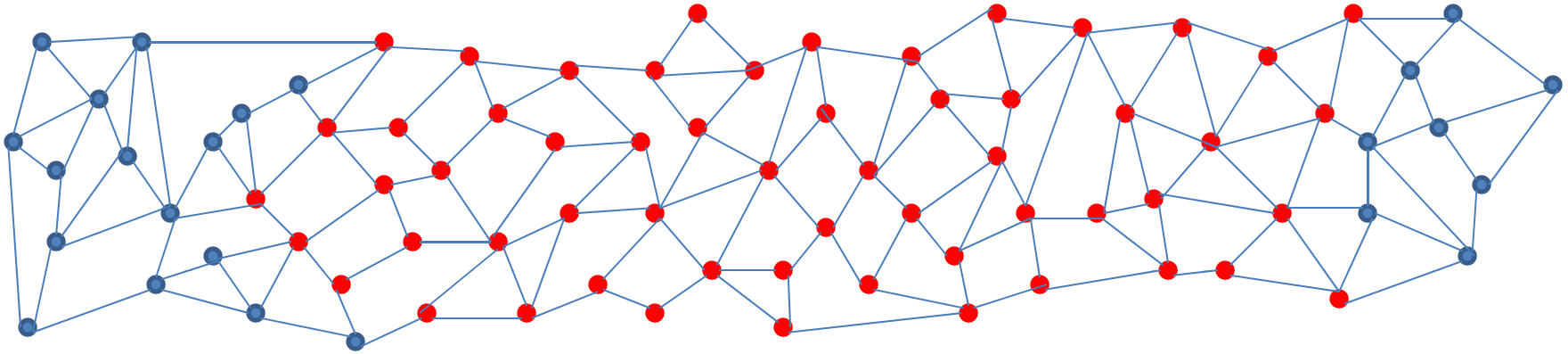

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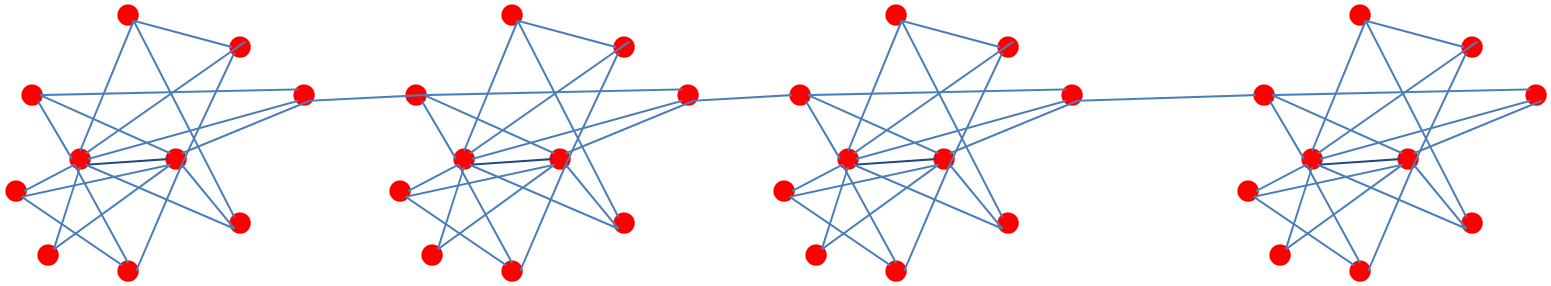

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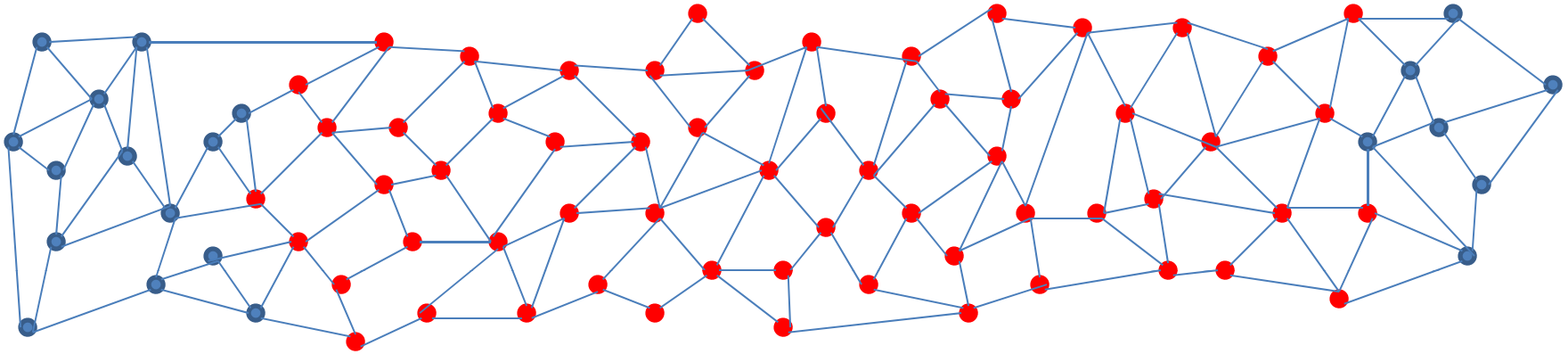

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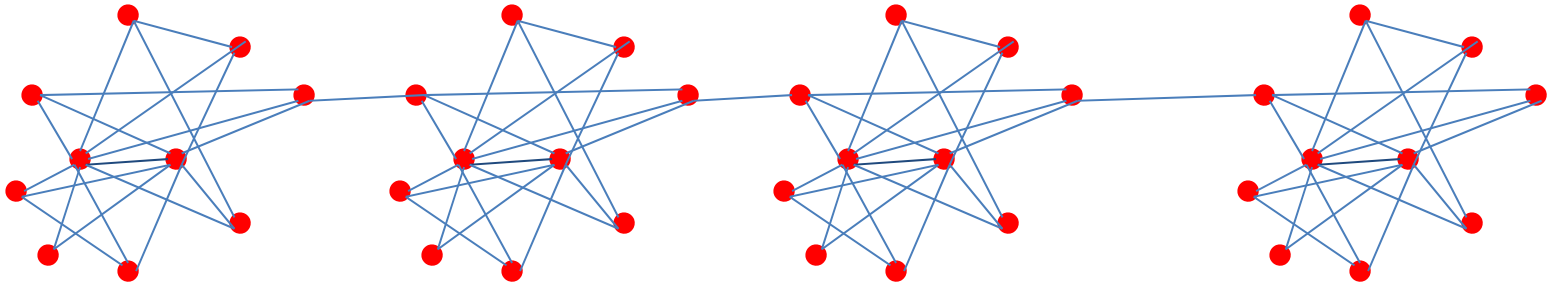

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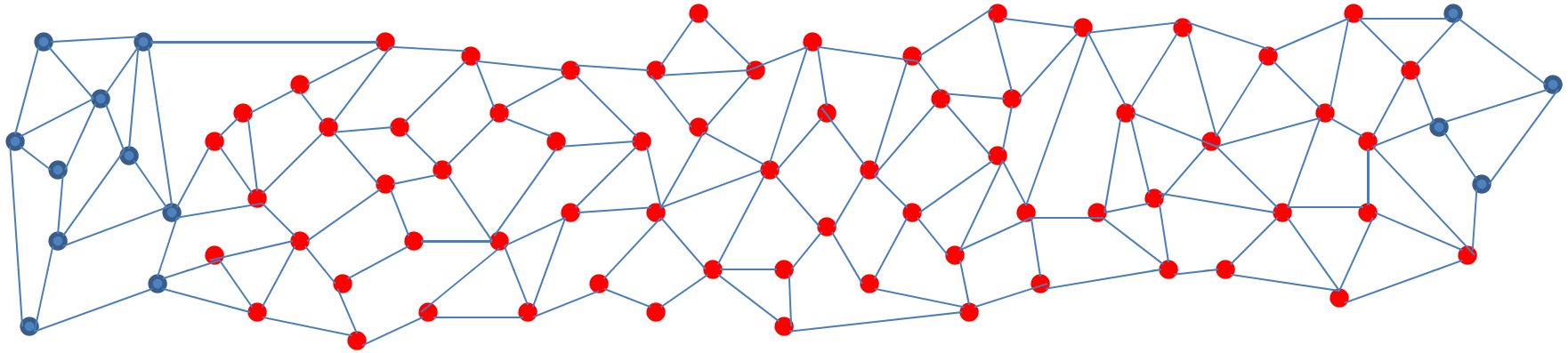

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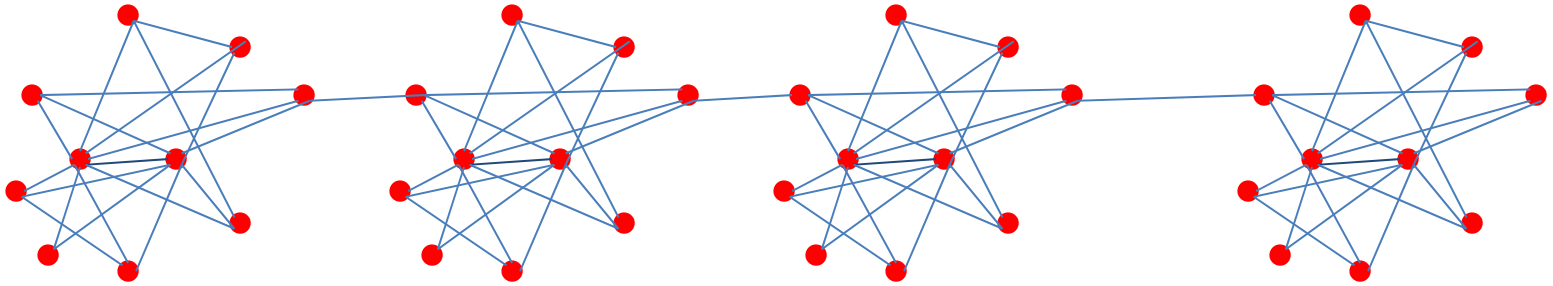

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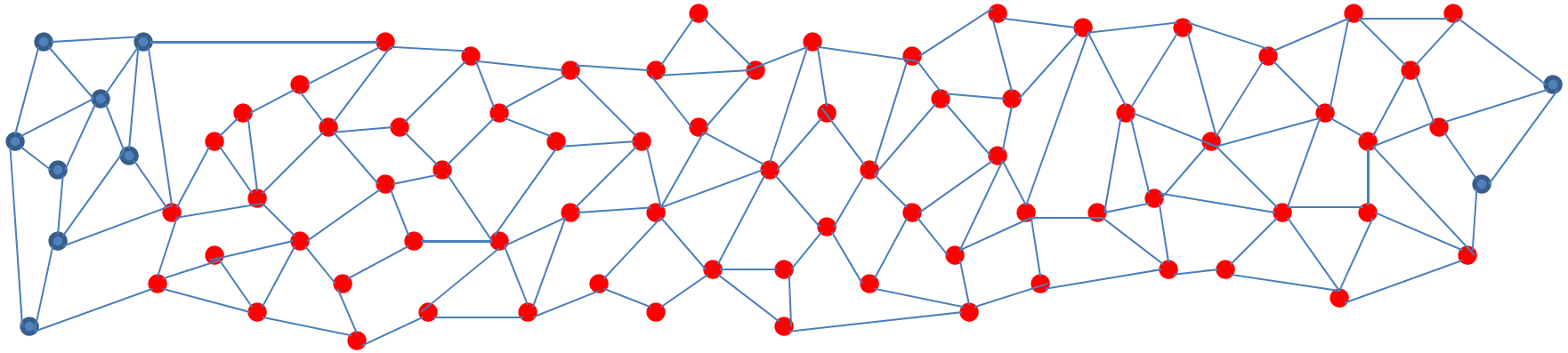

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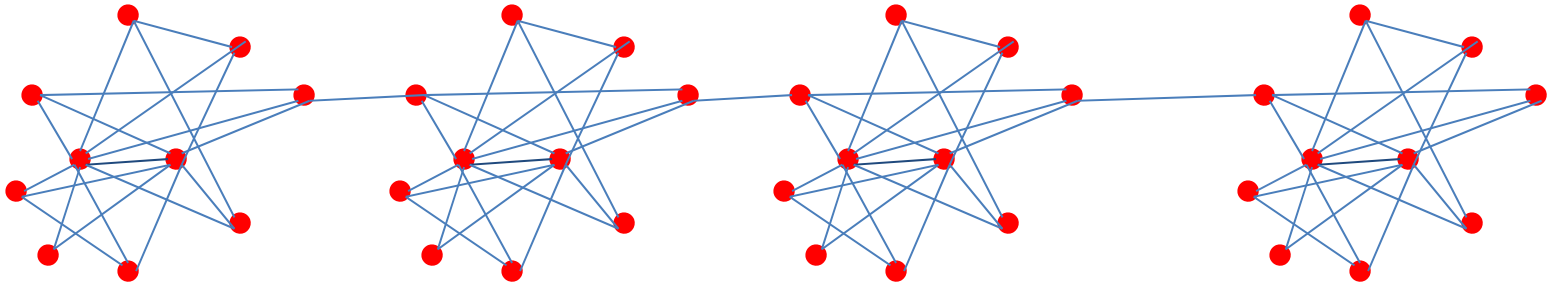

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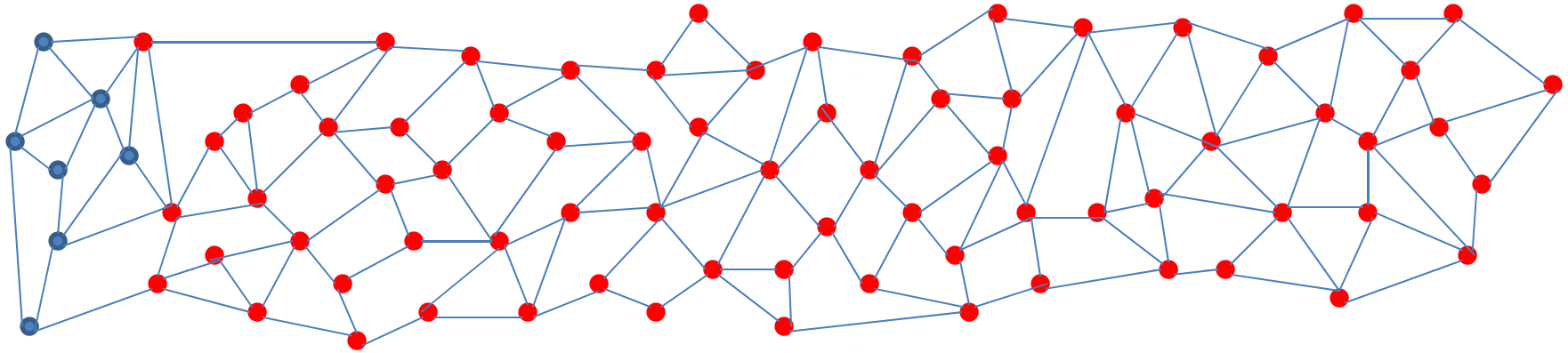

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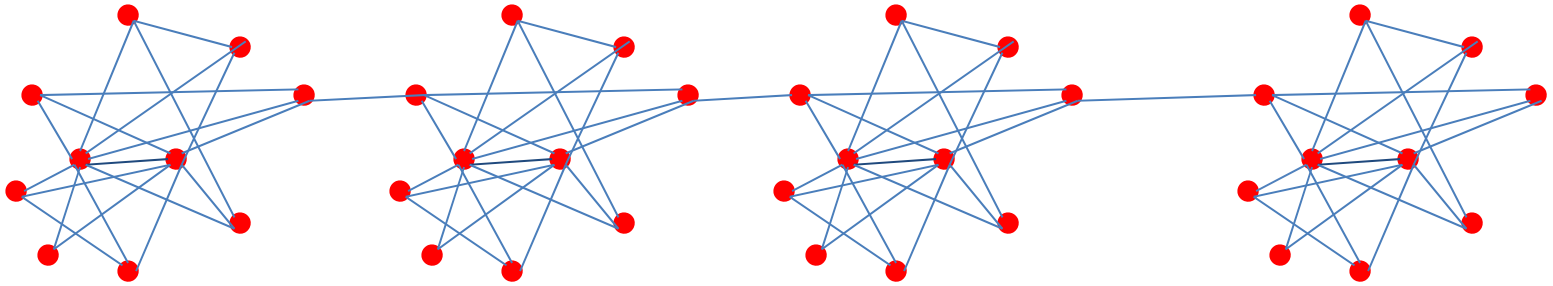

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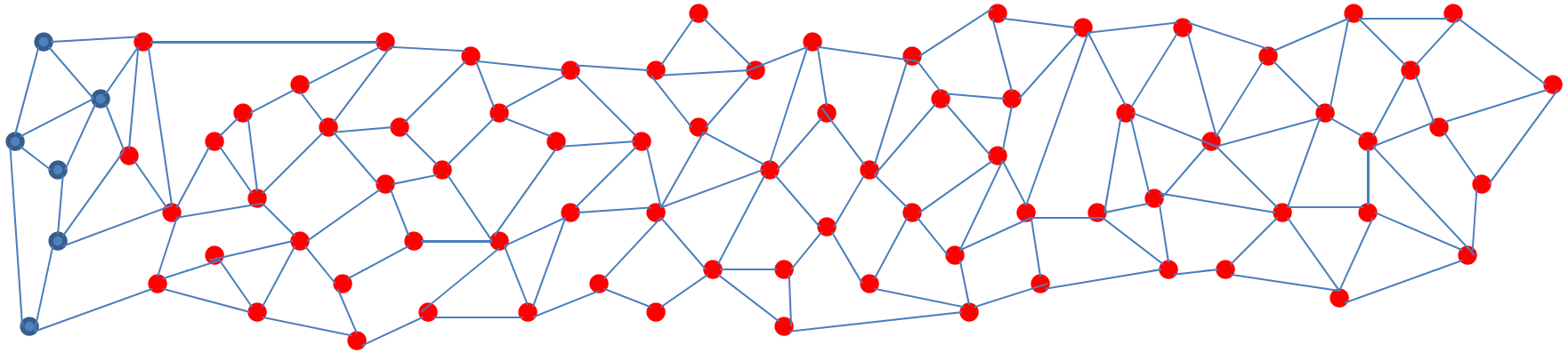

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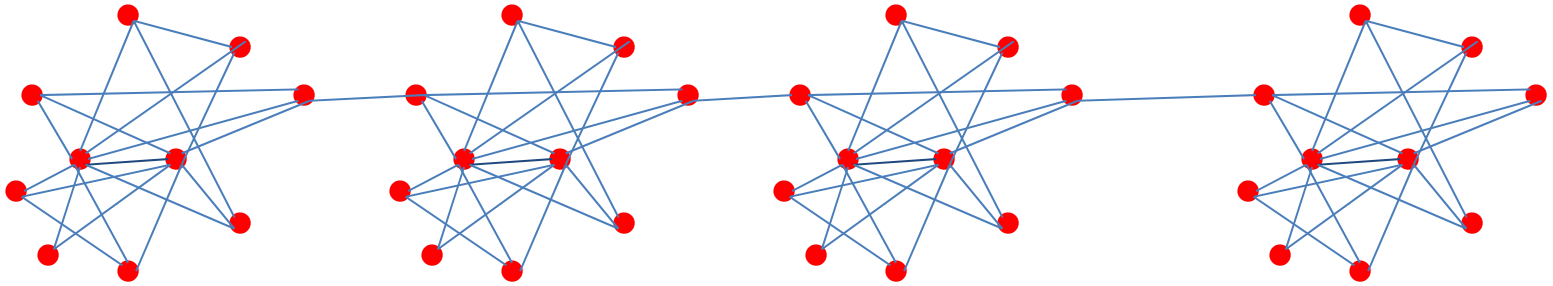

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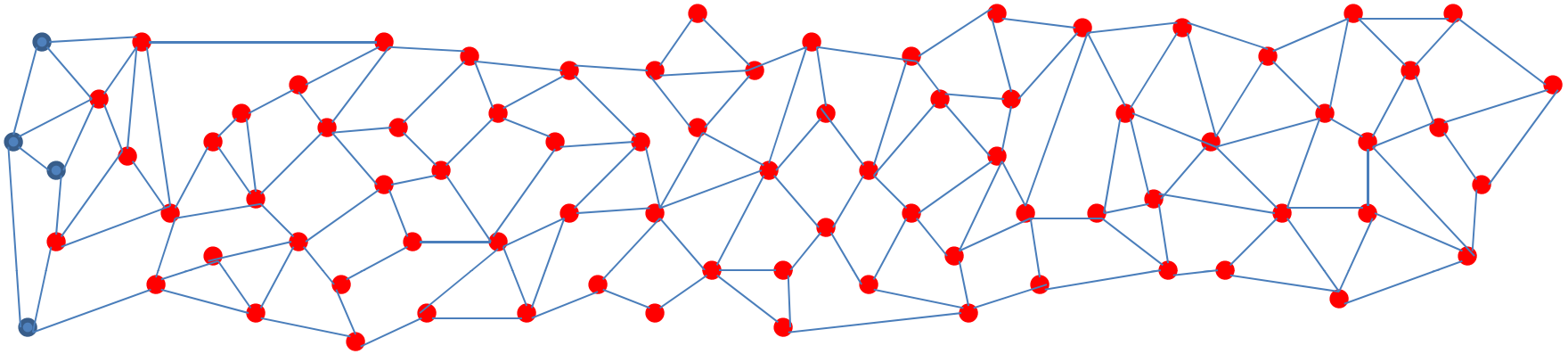

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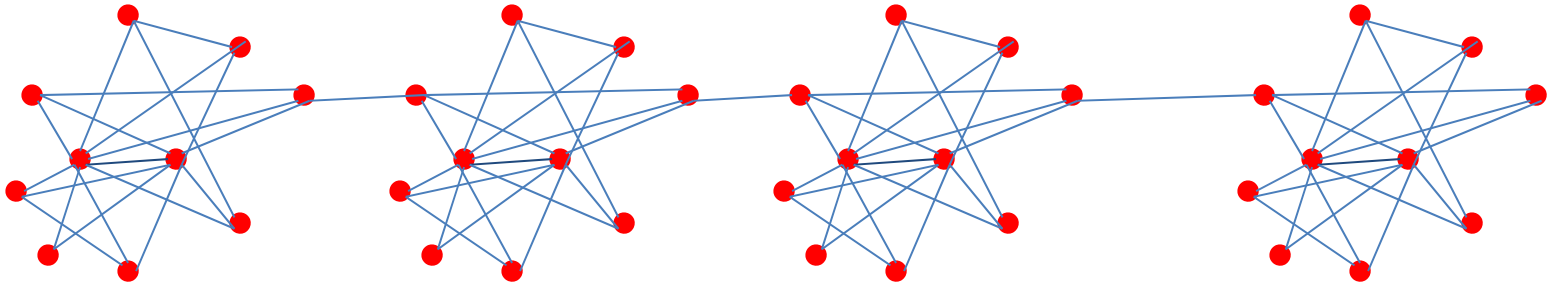

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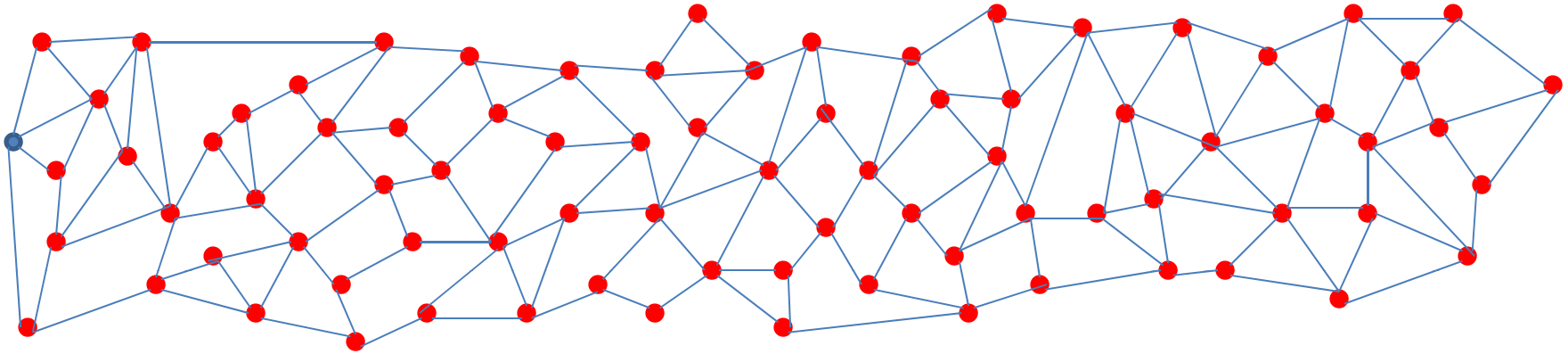

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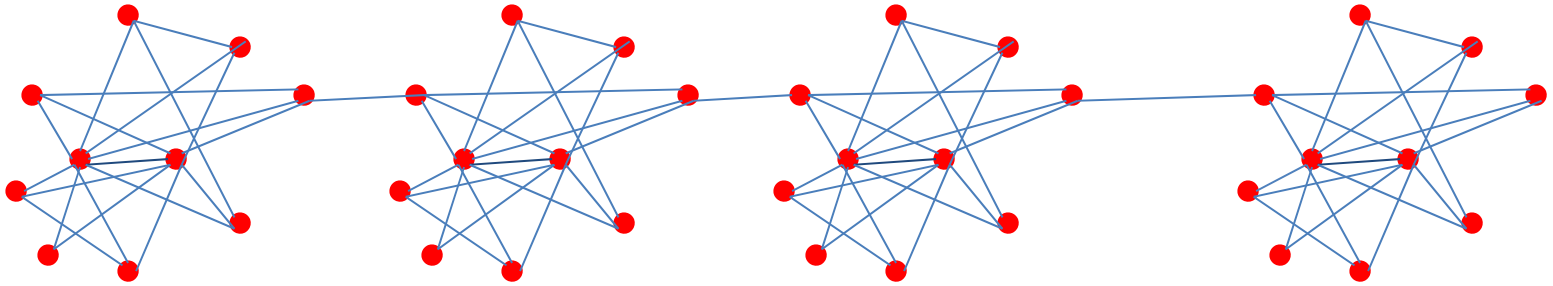

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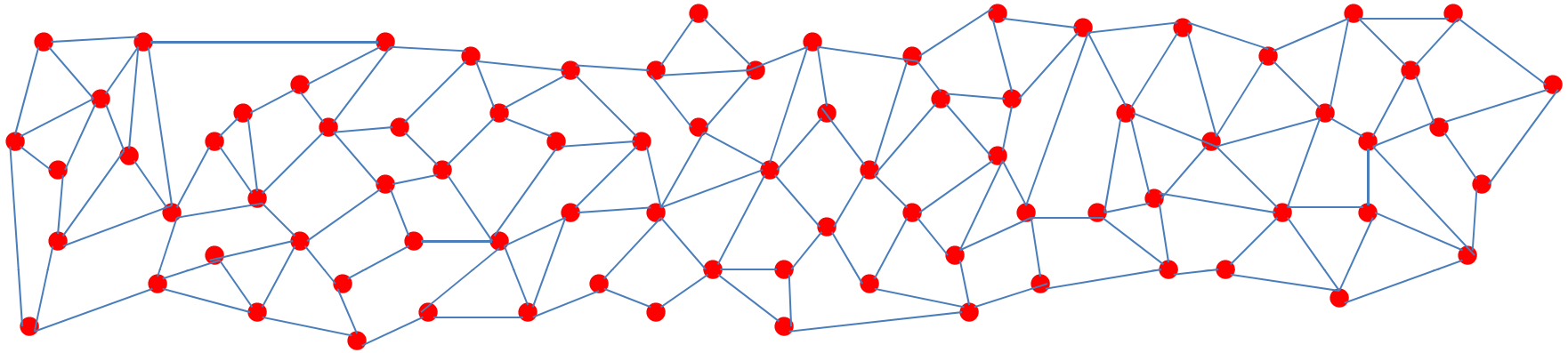

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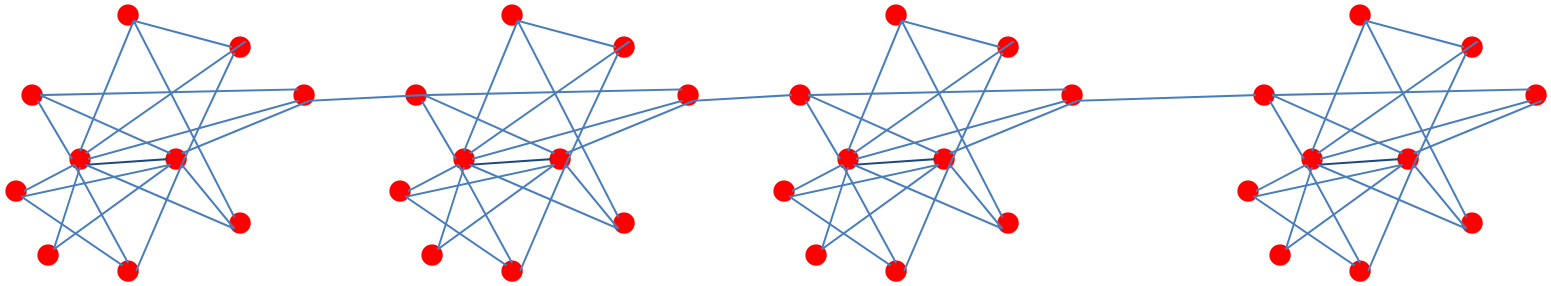


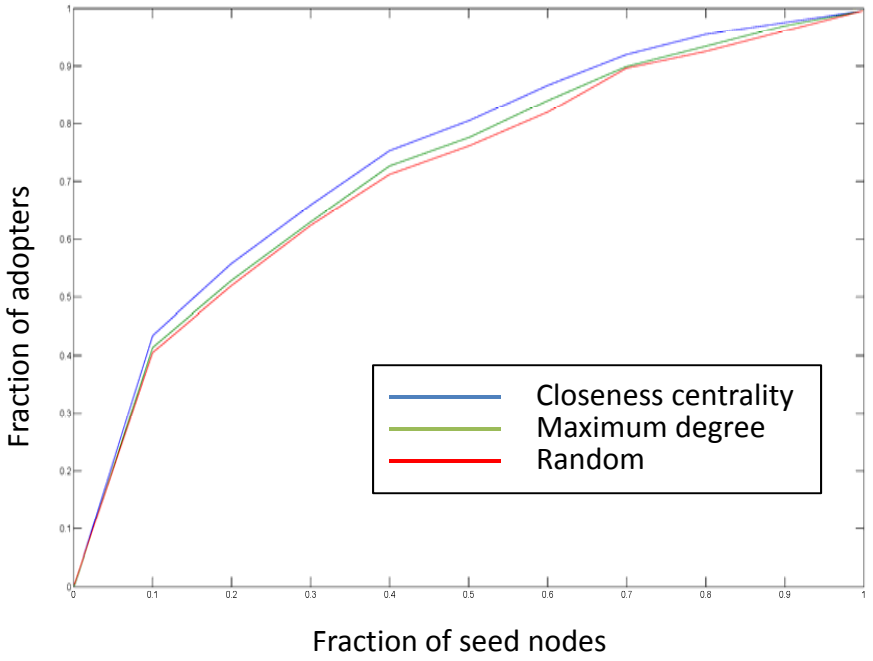
# Seeding Strategies

- Understanding the effect of *network structure* is important
- Three sample strategies
  - Random: No information on users or the network
  - Largest degree: Local user information only
  - Closeness centrality: Captures user and network information

# Final Adoption Levels

## 10,000 Node Generalized Random Graphs

Low-variance graph

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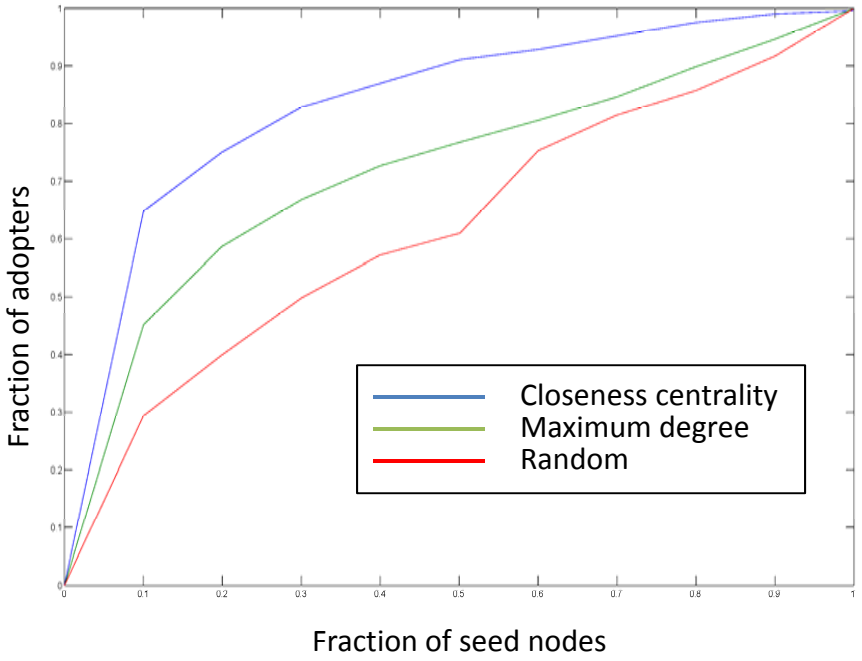
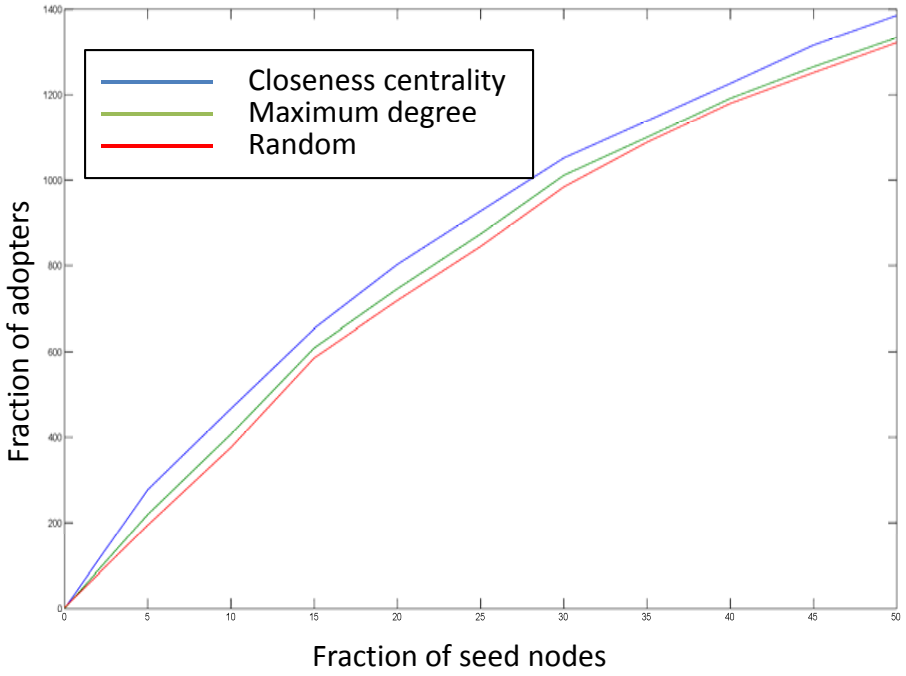


# Cascade Sizes

## 10,000 Node Preferential Attachment Graphs

Low-variance graph

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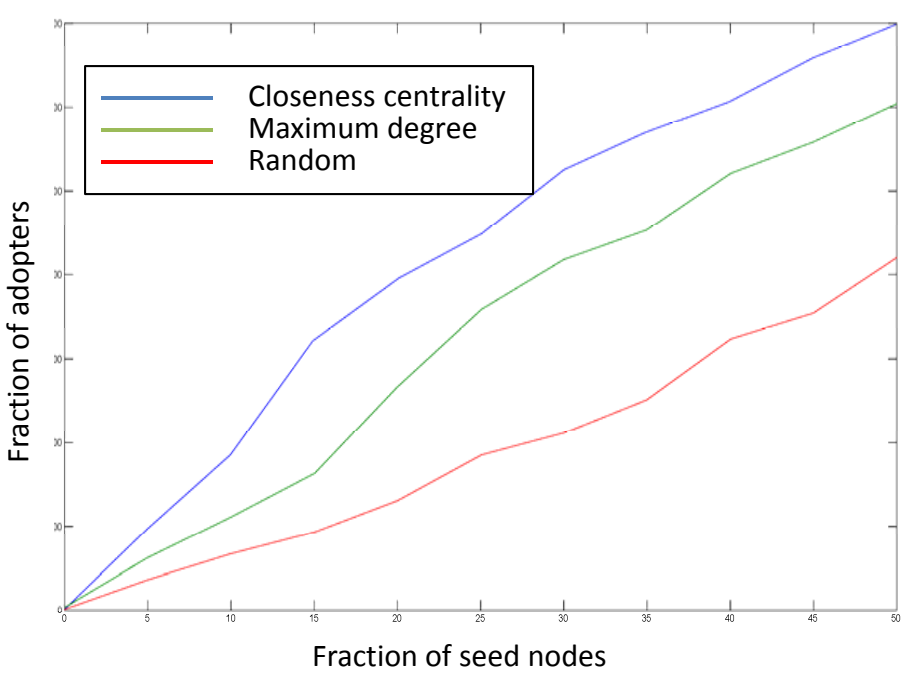

# Closing the Loop

- I did not say you don't/wont need a new network
  - And there is still quite a bit of fun stuff to do there
- I did say that
  - It better allow us do (or imagine doing) things we ***really*** want or need to do and cannot do with today's Internet
  - It better be ***much*** better to convince people to switch
- I also did say that
  - As the field of networking matures, many of the interesting problems arise in *using* networks not just *building* them
    - This is no different from what happens with most other technologies

# ACKNOWLEDGMENTS


- This talk is based on joint work with many colleagues and students, and has benefited from their inputs. In particular, I would like to acknowledge (in alphabetical order)

J. Corbo, K. Hosanagar, Y. Jin, A. Odlyzko, S. Sen, and Z.L. Zhang


Thank You!