

Network Theory: A Primer and Questions for Air Transportation System Applications

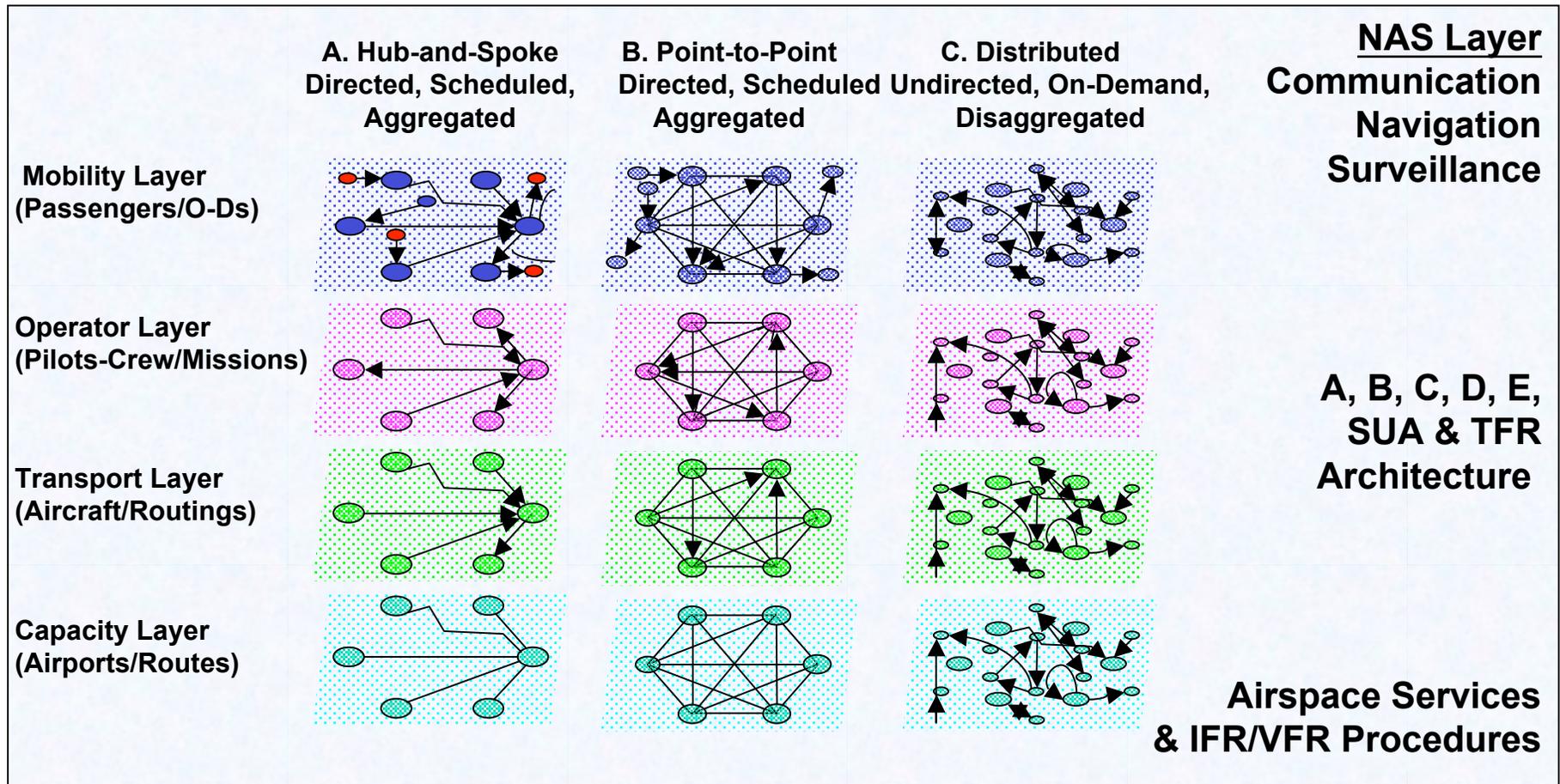
ABSTRACT

A new understanding (with potential applications to air transportation systems) has emerged in the past five years in the scientific field of networks. This development emerges in large part because we now have a new laboratory for developing theories about complex networks: The Internet. The premise of this new understanding is that most complex networks of interest, both of nature and of human contrivance, exhibit a fundamentally different behavior than thought for over two hundred years under classical graph theory. Classical theory held that networks exhibited random behavior, characterized by normal, (e.g., Gaussian or Poisson) degree distributions of the connectivity between nodes by links. The new understanding turns this idea on its head: networks of interest exhibit scale-free (or small world) degree distributions of connectivity, characterized by power law distributions. The implications of scale-free behavior for air transportation systems include the potential that some behaviors of complex system architectures might be analyzed through relatively simple approximations of local elements of the system. For air transportation applications, this presentation proposes a framework for constructing topologies (architectures) that represent the relationships between mobility, flight operations, aircraft requirements, and airspace capacity, and the related externalities in airspace procedures and architectures. The proposed architectures or topologies may serve as framework for posing comparative and combinative analyses of performance, cost, security, environmental, and related metrics.

Q: What network characteristics, topologies, and technology strategies would lead to scalable air transportation system behavior?

Proposed Topology for Air Transportation Networks

Q: What network characteristics, topologies, and technology strategies would lead to scalable air transportation system behavior?



Outline

“A problem well stated is half solved.”

- **Why Consider Network Theory?**
- **Research Issues**
- **“Aha’s” and Cautionary Notes**
- **Network Types**
- **Salient Analogies**
- **Scale-Free Networks (Small World Behaviors)**
- **Air Transportation Network Topologies and Lexicon**
- **Percolation, Diffusion, and Cascading and Organizational Architectures**
- **Robustness and Vulnerability**
- **Summary**
- **References**

Research Issues (Roadmap)

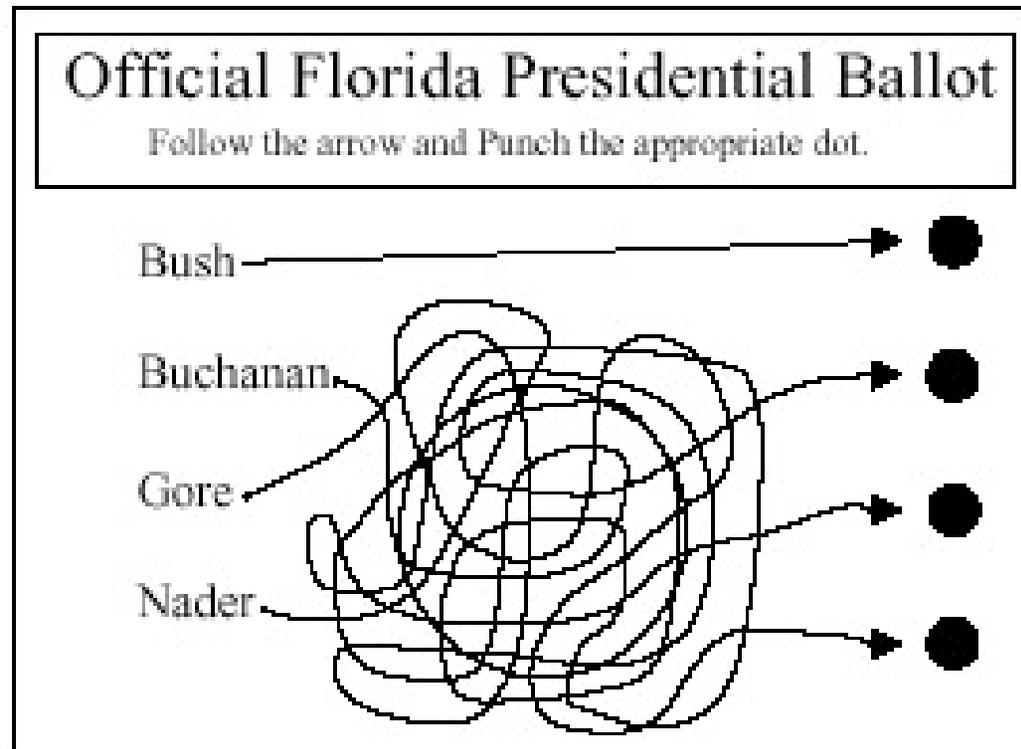
- **Validation of a topology as framework for transportation networks**
- **Establishment of a lexicon for transportation networks**
- **Network modeling and simulation tools and methods**
- **Demonstration problems in network-based transportation systems and architectures**

Why Consider Network Theory?

- **Network theory offers a framework for system-level thinking and analyzing air transportation architectures as networks.**
- **Network theory provides tools for quantitative analysis of certain network behaviors (cost, performance, robustness, vulnerability).**
- **The theory reveals the web-like relationships and “small world” behaviors that comprise many natural and human contrived systems.**
- **Network theory has implications to air transportation system component technologies (airframes, flight systems, airports, airspace-CNS, infrastructure).**
- **The theory offers a “constructionist” *versus* “reductionist” way of thinking at the system level.**

Network Diffusion/Percolation In a Scale-Free Network

Barabasi, 2002



How did 17,000 hits on Mike Collin's Webpage occur in one day?

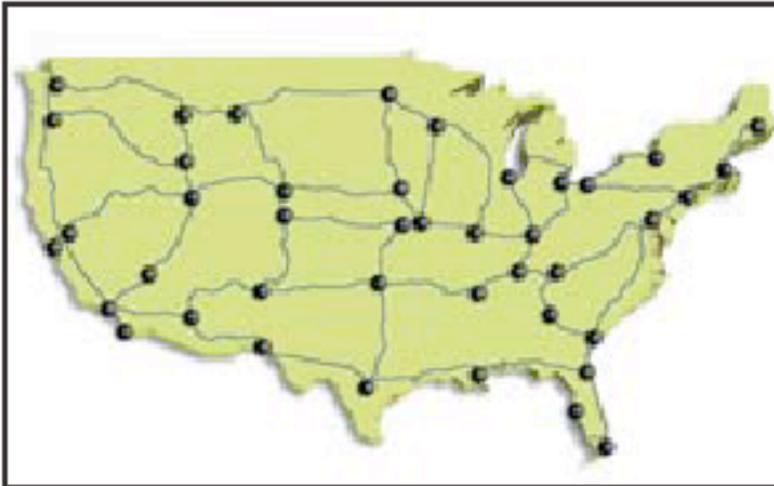
“Aha’s”

- **Air transportation topologies can serve in new ways to think about and articulate transformation, system innovation, methods and tools and scalability.**
- **Scalability (achievement of small-world behavior) can be a primal factor in air transportation innovation goal setting, at all layers in the topologies.**
- **The absence of air transportation topologies as mental models has confined much of our focus on only the infrastructure and transport layers in the architecture. The presence of a topology allows for better mental models of the linkages between mobility, operations, transport, and infrastructure layers.**
- **Power law distribution of nodes and links for infrastructure layer of air transportation topology can serve in new ways to think about the system layers:**
 - **Dis-aggregated on-demand mobility layer**
 - **Demand-adaptive operations/airspace layer**
 - **Decentralized infrastructure layer**
 - **Sizing of vehicles at the transport layer**
- **Organizational architectures must be impedance matched in order to take advantage of the diffusion properties of value webs in the delivery of products and services (*i.e.*, technology diffusion).**
- **Hierarchical systems engineering processes may not address the requirements architecture and management for complexity-based systems.**
- **System-level outcomes are better influenced by network-based value webs where component-level outcomes are better controlled by hierarchical value webs.**
- **Agent-Based Modeling (ABM) is a requisite capability to handle complex network behaviors. Object Oriented technology appears to facilitate ABM system development. System Dynamics approaches (alone) will not capture complex network behaviors.**

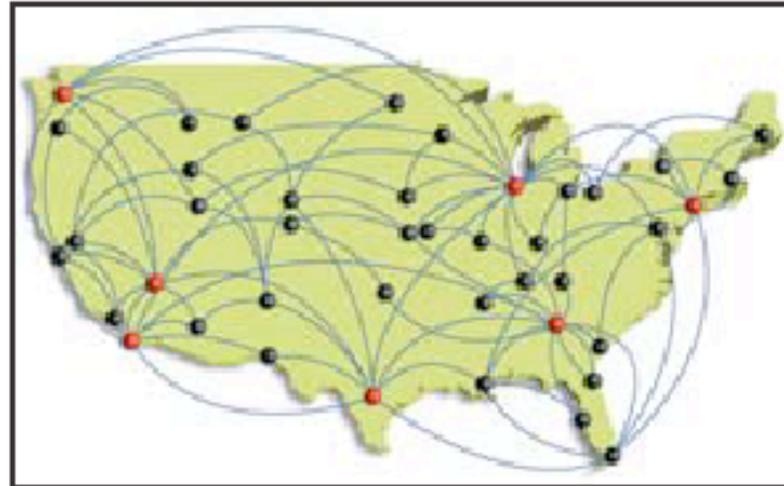
Network Types

(Barabasi & Bonabeau, Scientific American May 2003)

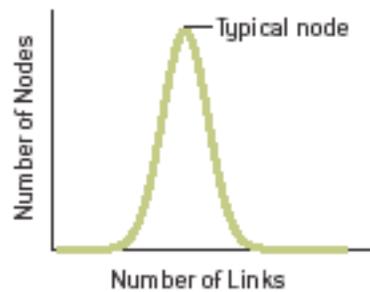
Random Network



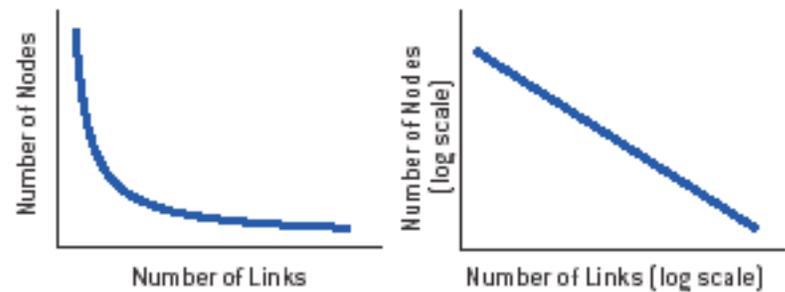
Scale-Free Network



Bell Curve Distribution of Node Linkages



Power Law Distribution of Node Linkages



Cautionary Notes

- **Modern science of networks is relatively new (~5 years in development).**
 - **Leaders in the field admit, “...prospects at times appear extraordinarily exciting at times, at other times, extraordinarily hard to accomplish...”; “As tempting as it is to overstate the significance of our findings, the truth is that most of the actual science here [in network theory] comprises extremely simple representations of extremely complicated phenomena.”**
- **System thinking (system of systems thinking) is a relatively young endeavor in general and in transportation specifically.**
 - **Practical implementation of theory in design of transportation networks is uncharted territory (only about 7 technical papers in air transportation)**
- **Any flaws in this presentation in the translation of the language of the science of networks into air transportation lexicon are the solely the responsibility of the author**
 - **Corrections, ideas, and new links are welcome!**

Definitions

Network Topic	Air Transportation Translation
<p>Aging (of nodes): Decreasing rate of attraction of new links by a node; limiting/prevention of the ability of preferential attachment to continue scale-free distribution of connectivity. All new nodes are “born” active, but may become inactive due to aging. Aging leads to cutoff of the power law decay of the tail of connectivity.</p>	<p>The saturation of capacity (or prohibitive cost of added capacity) in airports and airspace causes truncation of scale-free connectivity distributions (non-power law/exponential decay behavior). See <i>Small world structure/behavior</i> classes of characteristics.</p>
<p>Agent Based Modeling (ABM): System or network modeling based on collections of autonomous decision-making entities (agents), following prescribed rules for agent behavior and for interactions (links). ABM capable of capturing <i>emergent phenomena</i> in dynamic networks in nature.</p>	<p>JETWISE (MITRE Tool for scheduled airline evolutionary modeling) SWARM and 3-SWARM (freeware package for multi-agent simulation of complex systems) supported by Navy (NRL), DARPA, and Sandia TRANSIMS (transims.tsasa.lanl.gov) tool for ground traffic modeling; capable of determining <i>network reliability</i> (variability in doorstep-to-destination travel times).</p> <p>Agent Attributes (for supply and demand agents)</p> <ul style="list-style-type: none"> –Attributes –Rules of Behavior –Memory –Sophistication –Resources

Definitions, Continued

Network Topic	Air Transportation Translation
Aggregation (Hard and Soft)	<p>The hub-and-spoke and point-to-point scheduled air service models operate using aggregation of travelers</p> <p>The scale-free on-demand service model operates using dis-aggregation of travelers.</p> <p>Soft aggregation is the collection of more than one traveler through options in the service business model.</p>
Clusters/Clustering Coefficient: The probability that two classes that are neighbors of a given class are neighbors of each other; ratio of actual over possible links (e.g., the ratio of the probability that your friends know each other to the probability that two randomly selected people know each other).	<p>The Hub-and-Spoke system exhibits strong clustering behavior (it is possible to connect between any two of the airports in the world through a very small number of links - network diameter = ~4-5); small clustering coefficient</p> <p>Netjets fractional ownership operations exhibit weaker clustering behavior (it is possible to connect between any two of the airports in the world with one link); Clustering coefficient approaches 1.0</p>
Constraints: Limits on performance attributes of behavior of nodes and paths between nodes (links)	
Degree distribution: Log-log slope of links vs.nodes; constant slope for scale-free networks, non-linear slope for random networks.	

Definitions, Continued

Network Topic	Air Transportation Translation
<p>Degrees of Separation (d): The ratio of the logarithms of the number of nodes (N) over the number of links (k) $d = \log N / \log k$ (for a random network); $d = 0.35 + 2 \log N$ (e.g., for the scale-free World Wide Web)</p>	
<p>Diffusion: Process by which phenomena (innovations, infections, etc.) move through a network, from early adopters to explosive growth (global cascades), then to maturing/die-off.</p>	<p>Along with <i>Percolation</i> and <i>Cascading</i>, diffusion explains shaping of S-curves for innovation life cycles and transportation mode substitution/diversion behavior.</p>
<p>Directed Networks: Irreversible, deterministic, synchronous, scheduled behaviors and processes, e.g., chemical reactions; WWW (HTML)</p>	<p>e.g., in centralized or point-to-point scheduled transportation systems, transport, operation, and mobility layers are fixed, not flexible e.g., TDMA versus CDMA</p>
<p>Emergent phenomena: System behavior which involves non-intuitive, non-linear consequences of interactions between individual entities in a network, caused by the interactions themselves, therefore cannot be predicted by static characteristics (the whole is more than the sum of its parts; also see <i>cascading</i>)</p>	<p>Some debate as to appropriateness of term “emergent.” Whether behavior is emergent, or merely inadequately anticipated is at issue. The term “unanticipated” behavior may be more useful for transportation systems.</p>
<p>Erdos Number: Degrees of separation between mathematician Paul Erdos and other mathematicians in publication citations</p>	

Definitions, Continued

Network Topic	Air Transportation Translation
Fitness: In a competitive network environment, fitness defines the ability of nodes to attract links (preferential attachment)	<p>Candidate fitness metrics for air transportation nodes should be developed for all layers (mobility, operation, transport, and capacity)</p> <p>For air transportation, node fitness would be a product of:</p> <ul style="list-style-type: none">– Gravity Model parameters (population density, propensity to travel, distance between nodes)– Proximity of airport to trip origin and ultimate destination, with near all-weather runway capability, weather characteristics at O&D (probability of successful trip completion)– Availability of transportation service within constraints of frequency of service and cost of service (probability of successful trip initiation)– Modal choice preference factors (probability of mode choice)

Definitions, Continued

Network Topic	Air Transportation Translation
<p>Fitness Landscape: (Smooth; Static; Flat; ...)</p>	<p>In transportation, a fitness landscape would be represented by the time-dependent, geographic distribution of both gravity model distributions and runway/community air accessibility distributions.</p> <p>Fitness landscapes in on-demand transportation systems could display asset allocation information (aircraft, pilots, parts, limos, lunches, etc.) against demand density distributions (populations of travelers) that satisfy return on investment thresholds.</p>
<p>Fitness Connectivity Product: In <i>Scale-Free</i> network, the probability of connection of a new node to a node of k links is $P \sim k/\sum k_i$. In Fitness-based network, the probability is influenced by the nodes' fitness, f; thus, the probability is $k f / \sum k_i f_i$.</p>	
<p>Graph Theory: Use of mathematical objects called <i>graphs</i>, of connections between nodes and links to developed by Leonhard Euler (1736) as the theory of random graphs</p>	

Definitions, Continued

Network Topic	Air Transportation Translation
<p>Growth: In a <i>Scale-Free</i> network, rate of growth (of new nodes and new links) is proportional to the square root of time, t^{-2}; in a <i>Fitness-based</i> network, the rate at which nodes acquire links still follows a power law, t^{β}, where the dynamic exponent, β, measures how fast each node acquires new links.</p> <p>What makes modern network science truly new is the understanding that networks are dynamic, that networks depend on what happened previously, and that networks can be viewed as integral parts of a continuously evolving and self-constituting system. The most highly connected nodes exhibit the fastest growth (up to the limits caused by <i>aging</i>). <i>Preferential attachment</i> is a requisite characteristic of scale-free growth.</p>	<p><u>Candidate Definitions:</u></p> <p>Mobility Layer:</p> <ul style="list-style-type: none"> •Accommodation of growing numbers of agents (travelers, packages, ...), especially in dis-aggregated transportation services <p>Operation Layer:</p> <ul style="list-style-type: none"> •Adaptation of operations and business models to varying requirements for crew (two-pilot; single-pilot; self-crewed; un-crewed) <p>Transport Layer:</p> <ul style="list-style-type: none"> •Demand adaptive accommodation of growing numbers of aircraft on short-term and long-term time scales <p>Capacity Layer:</p> <ul style="list-style-type: none"> •Accommodation of growing numbers of airports/runway ends accessible in the NAS

Definitions, Continued

Network Topic	Air Transportation Translation
<p>Heterogeneous Nets: Networks comprised of dissimilar elements, layers, processes. Open architectures support interoperability in <i>h. nets</i>. Such nets exhibit extremely resilient behavior under random failure, at the same time as exhibiting increased vulnerability to attack</p>	<p><u>Candidate Definitions:</u> Multiple, interoperable topologies (directed, undirected, centralized, distributed, scheduled, on-demand, synchronous, asynchronous) for:</p> <ul style="list-style-type: none"> • Capacity Layer = Comm-Nav-Surveillance (NAS) architectures; • Transport Layer = Aircraft fleet mix • Operation Layer = Two-crew; single-crew; self-operated; un-inhabited • Mobility Layer = Transportation service business models (scheduled, on-demand, ...); transport function (people, packages, services, ...)
<p>Hubs (in networks): Clusters that are “fitness” derived, gaining links through <i>preferential attachment</i></p>	<p>Hub and Spoke airports in scheduled airline travel Dynamically-formed higher-density airports in on-demand SATS-taxi services.</p>
<p>Multi-Scale Networks:</p>	

Definitions, Continued

Network Topic	Air Transportation Translation
<p>Network Diameter: Degrees of Separation; increases logarithmically with the number of nodes. If 100 of my friends have each 100 friends, who in turn each have 100 friends, then I am connected to $100 \times 100 \times 100 = 1 \times 10^6$ acquaintances by four degrees of separation (four links, including myself). If each of the fourth tier of friends has 100 friends who each have 100 friends, then I am connected to $100 \times 100 \times 1 \times 10^6 = 10 \times 10^9$ acquaintances by six links (thus Six Degrees of Separation).</p>	

Definitions, Continued

Network Topic	Air Transportation Translation
<p>Network Reliability: Variability in performance of network. Loss of reliability produces one source of system “waste,” in a six-sigma sense.</p>	<p><u>Candidate Definitions:</u></p> <ul style="list-style-type: none"> • Mobility Layer: Variability in transit times from doorstep-to-destination • Operation Layer: Labor dispute effects; Labor rules effects; ... • Transport Layer: Delays/holds;... • Capacity Layer: Weather effects; terrorism effects; ... • CNS Layer: Delays in communication, navigation, and surveillance services, ... <p>Sources of loss/lost reliability (waste) in airspace systems:</p> <ul style="list-style-type: none"> • Missed approaches • ATC Preferred Routes (<i>versus</i> “least wind miles”) • Runway occupancy limits • Terminal departure fix loading • Radar-based separation • Miles-in-trail arrival spacing • Single file (no passing) • Ground delays • Refiling requirements

Definitions, Continued

Network Topic	Air Transportation Translation
<p>Nodes: Vertices in networks with characteristics of: <i>aging</i>, competition, clustering, decision-making, filtering, <i>fitness</i>, knowledge, links, cost. Nodes can be active or inactive (see <i>Aging</i>), with inactive nodes unable to gain new links.</p>	<p><u>Candidate definitions:</u></p> <p>Mobility Layer:</p> <ul style="list-style-type: none"> • Nodes = Originations from points of departure • Links = Trips to destinations <p>Operation Layer:</p> <ul style="list-style-type: none"> • Nodes = Pilots; crew • Links = Mission profiles and labor rules/constraints <p>Transport Layer:</p> <ul style="list-style-type: none"> • Nodes = Aircraft (within the vehicle, additional topologies can be defined for structures, sensors, power distribution, controllers, computers, local networks, off-board datalinks) • Links = ATC communication; Radar surveillance; ADS-B, Airborne Internet <p>Capacity Layer:</p> <ul style="list-style-type: none"> • Nodes = Airports • Links = Jet routes, departure and arrival procedures, free-flight routes

Definitions, Continued

Network Topic	Air Transportation Translation
<p>Percolation (in network): An <i>emergent phenomenon</i>, the transition from independent behavior of nodes to group behavior of an entire cluster (in sociology, the formation of a community; in mathematics, the emergence of a giant component that includes a large fraction of all nodes)</p>	
<p>Phase Transition: Occurs when the network experiences a global cascade or transition of virtually all nodes to a new network characteristic. For example:</p> <ul style="list-style-type: none"> – From liquid to solid (e.g., water to ice) – Bose-Einstein Condensate 	<p>Challenge Problem: In an on-demand, un-directed, disaggregated transportation network, what number of aircraft, serving what number of nodes, at what levels of cost and performance, will create a transition in phase as evidenced by the following system behavior shifts:</p> <ul style="list-style-type: none"> – From most legs empty to most legs full – From loss to profit – From most consumers not knowing about the on-demand choice to most consumers understanding the choice

Definitions, Continued

Network Topic	Air Transportation Translation
<p>Power Law Distribution: Plotted as # of nodes with k links <i>versus</i> # of links (k), hyperbolic distribution for a scale-free network; contrasted with normal (e.g., Gaussian or Poisson) exponential distribution for a random network</p>	<p>In real-world air transportation network behavior, the capacity layer (airports and air-routing links) exhibits cutoff of the distribution of connectivity due to capacity constraints in the hub-and-spoke system. This class of <i>small-world behavior</i> is <i>broad scale or truncated</i>, exhibiting an exponential cutoff of the tail of the distribution of connectivity.</p>
<p>Preferential attachment (of nodes): Distance, time, cost, or other performance attributes of network behavior between nodes. Leads to formation of Hubs (See <i>Hubs and Fitness</i>). Gives rise to the <i>power law distribution</i> of connectivity. Preferential attachment and growth support hub-dominated, <i>scale-free</i> topologies. In a competitive network environment, <i>preferential attachment</i> is driven by the product of the node's fitness and the number of links it has (see <i>Fitness Connectivity Product</i>).</p>	<p>Growth by preferential attachment would be enabled through on-demand behavior of user-preferred schedule, point of origin, point of destination, and routing.</p>

Definitions, Continued

Network Topic	Air Transportation Translation
<p>Re-wiring: Adaptability of <i>scale-free</i> networks illustrated by the creation of short-cuts.</p>	<p>Demand-adaptive system concepts for transportation services may exhibit scale-free behaviors in the mobility layer.</p>
<p>Robustness (related terms: reliability, vulnerability, resilience)</p>	<p>On-demand transportation networks will require robustness in system performance (time-of-service windows, denial-of-service rates). The robustness of an on-demand network will depend on tolerance of the network to variability in temporal and spatial dynamics of demand and of weather, equipment and crew positioning, etc.</p>
<p>Scale-Free Topology: A basic feature common to complex networks whereby a microscopic structure and a macroscopic structure appear the same; when small bits of the network are magnified, they resemble the whole.</p> <p>See comments on resilience under “<i>Heterogeneous Nets.</i>”</p> <p>Scale-free networks emerge under conditions of network <i>growth</i> with <i>preferential attachment</i> between nodes.</p>	<p>Demand-adaptive system concepts for comm-nav-surveillance architectures and airspace procedures may exhibit scale-free behaviors in the capacity and transport layers.</p> <p>Scale-free in air transportation means that a service operating schedule could be responsive in “real time” to fitness-based, preferential attachment by links between nodes; that is, trips are on-demand schedule requirements by traveler between O-Ds, not based on providers’ schedules.</p>

Definitions, Continued

Network Topic	Air Transportation Translation
<p>Scalability (of networks): The ability of the network to grow by preferential attachment, as enabled through nodal fitness.</p>	<p>Scalability by layer in a notional air transportation topology would be enabled at each layer by certain technology strategies, for example:</p> <p>Physical (airports) Layer: Scalability would be enabled by technologies that enable every runway end to be equally approachable in common weather conditions.</p> <p>Transport (aircraft) Layer: Scalability would be enabled by lower total operating cost per unit payload/speed for aircraft in fleet operations.</p> <p>Operations (crew, controllers) Layer: Scalability would be enabled by technologies that reduce the burden (cost, complexity) placed on the network by crew and controller requirements (e.g., single pilot or non-piloted aircraft; airspace operations with reduced controller interaction requirements).</p> <p>Mobility (travelers, cargo) Layer: Scalability would be enabled by user-preferred schedules (on-demand) and points of origin and destination.</p> <p>National Airspace System (NAS architecture, procedures, services) Layer: Scalability would be enabled by demand-adaptive technologies such as airborne-centric capabilities for separation and sequencing.</p>

Definitions, Continued

Network Topic	Air Transportation Translation
<p>Small World Structure/Behavior: A basic feature common to <i>scale-free</i> networks wherein they exhibit (a) <i>clustering coefficients</i> larger than random networks, and (b) the <i>network diameter</i> (degree distribution) increases logarithmically with number of nodes. Any constraint limiting the addition of new links is a controlling factor for the emergence of <i>scale-free</i> behavior.</p>	
<p>Three classes of <i>small-world behavior</i> are in the literature: (1) <i>Scale-Free</i> Networks decay with power-law, (2) <i>Broad-Scale</i> Networks decay with power-law followed by a sharp cutoff, and (3) <i>Single-Scale</i> Networks decay with a fast-decaying tail/minimal power law segment.</p>	<p>SATS notionally exhibits a greater degree of scale-free behavior for air transportation than other modes Hub-and-Spoke notionally exhibits <i>Single-Scale</i> network behavior (Note: Is it acceptable to build composite depictions of power-law groupings for the three classes of small-world behavior?)</p>
<p>Topology: architecture of relationships between nodes and links; can be emergent or self-determined in scale-free networks</p>	

Definitions, Concluded

Network Topic	Air Transportation Translation
Undirected Networks: Reversible, non-deterministic, asynchronous behavior and processes	e.g., on-demand, distributed transportation systems; transport layer routings not fixed; mobility layer routings flexible e.g., CDMA <i>versus</i> TDMA

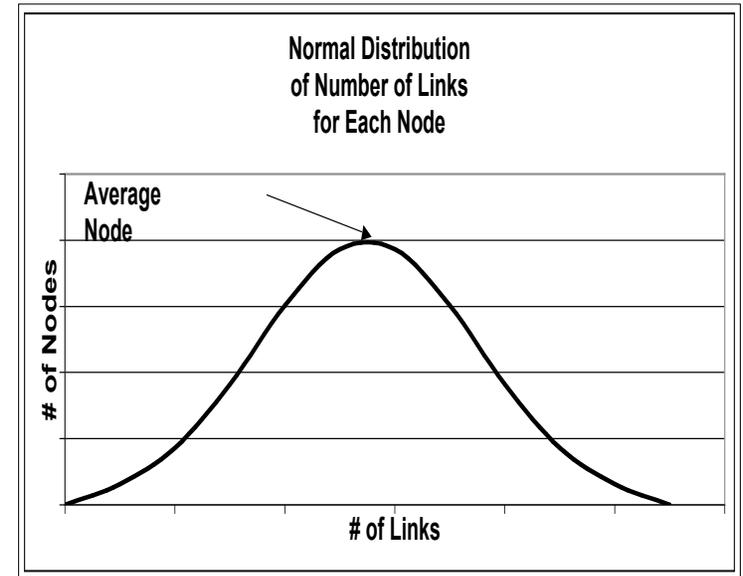
Scale-Free Networks (Small Worlds)

- **The signatures of Scale-free networks include:**
 - **Small-world behavior (degrees of separation)**
 - **Power-law distributions of links between nodes**
 - **Constant clustering coefficient**
- **Small world networks can be scale free to varying degrees**
- **Small world networks exhibit dynamics (network growth by preferential attachment)**

Scale Free Networks -- Characteristics

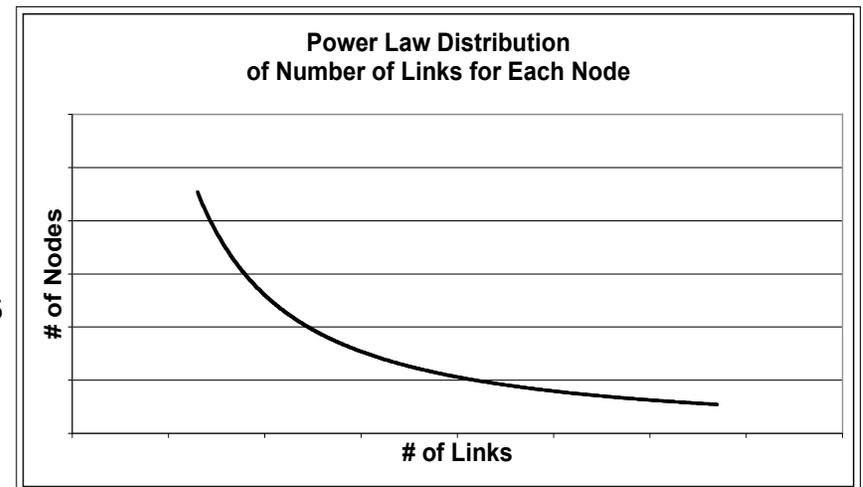
Power Law Behavior

- We thought that normal-type (or Poisson) probability distributions were how the degrees of distribution of # of links for each node in networks could best be modeled. This thought was based on our belief that networks were generally random, with the largest number of average nodes being highly connected and the fewer number of nodes being poorly connected.



This turns out to be incorrect.

- Power law distributions characterize the degrees of connectedness of nodes by # of links for most all networks of interest. These networks are scale-free with most nodes being poorly connected and a few nodes being highly connected.



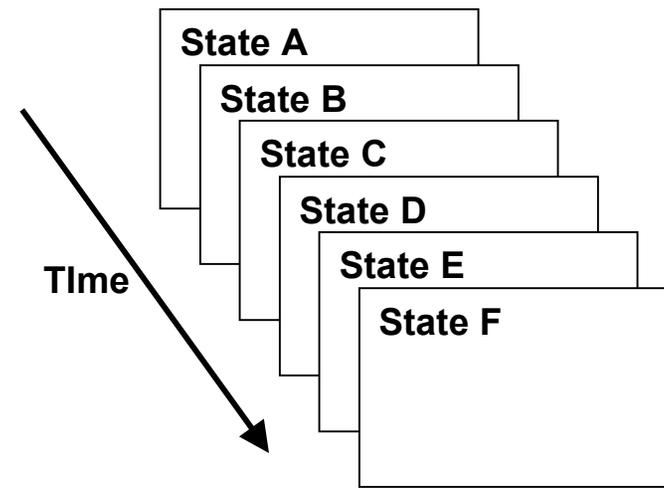
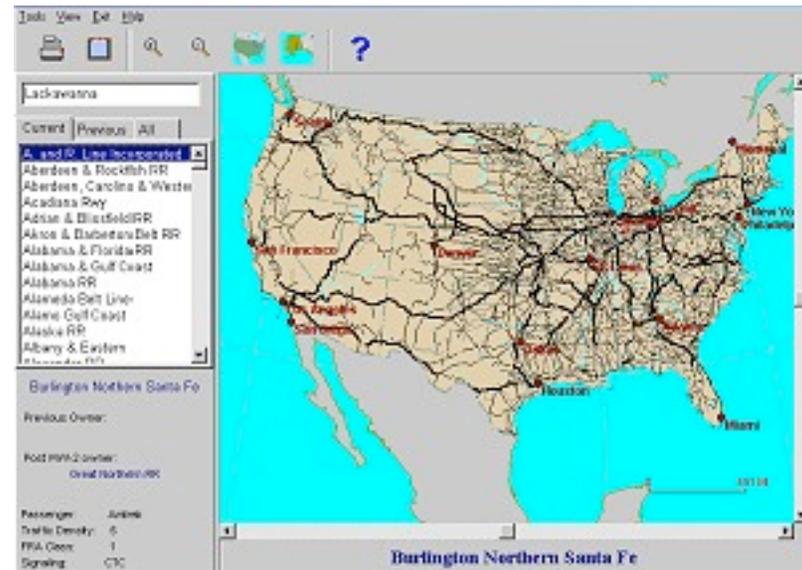
Scale Free Networks -- Characteristics

Dynamic Behavior: Evolution and Growth

- We thought that static network models were adequate to understand network behaviors.

It turns out this is incorrect.

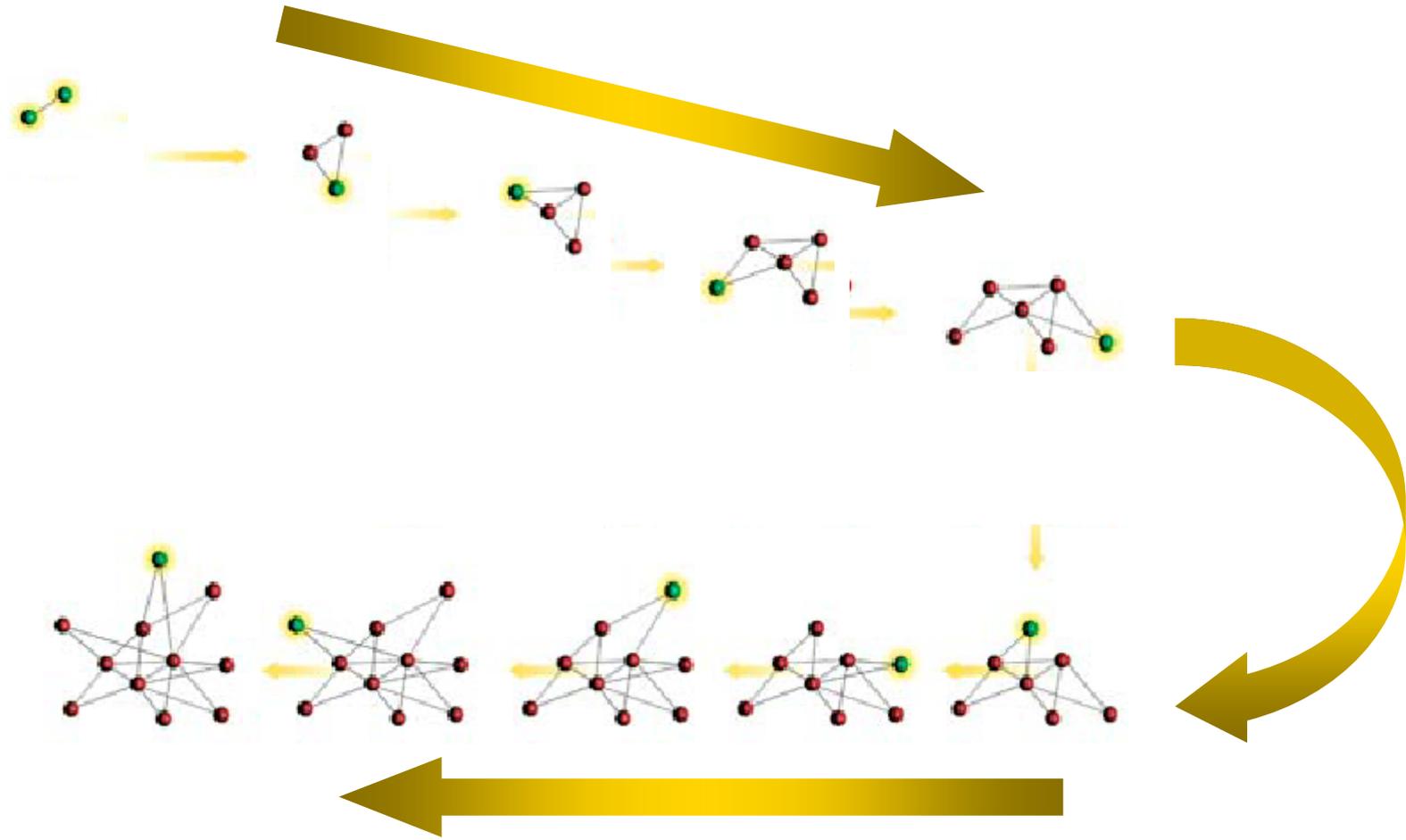
- Networks of interest (scale-free) evolve, grow, have time-dependence. The current state of scale-free networks depends on what went on in the network before. What follows next in a scale-free network includes preferential attachment based on the current state of the network.



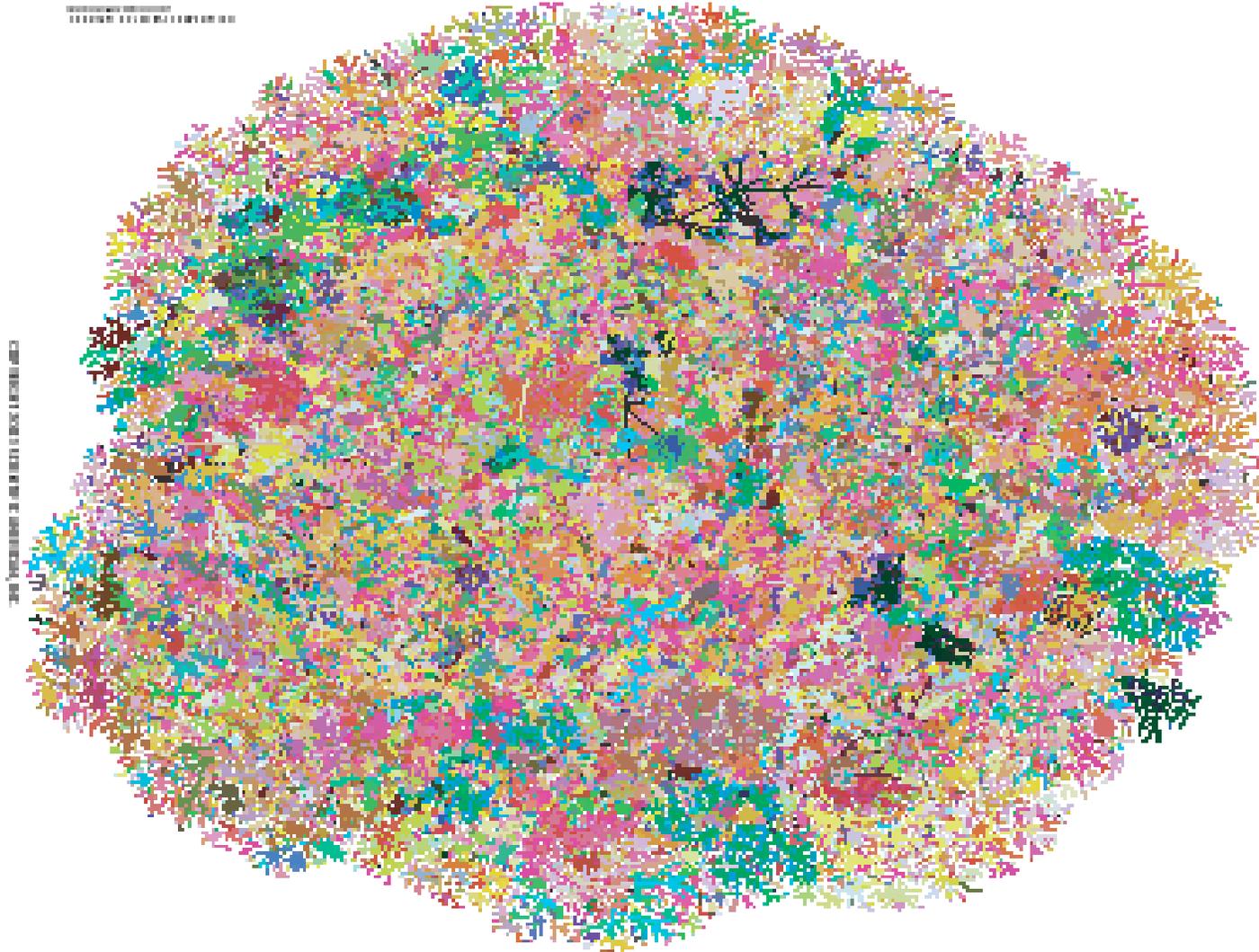
Salient Mathematical Analogies (Network Diameter)

- **Bose-Einstein Condensate (& phase changes)**
- **Brain/neural processes (14 synapses in *C. elegans*)**
- **Biological Cellular Networks (3)**
- **Chemical reactions (rates of diffusion)**
- **Efficient Software Architectures**
- **Fads and manias (social behaviors)**
- **Food chains-webs (2)**
- **Hollywood (Kevin Bacon game)**
- **Investment bubbles**
- **Language (nodes = words; links = co-occurrences)**
- **Lexical Networks (links in word usage)**
- **Metabolism**
- **Power Grids (cascading failures)**
- **Railroads**
- **Stock Market (bubbles)**
- **Scientific Collaborations and Citations (4 to 6)**
- **World Wide Web (19)**

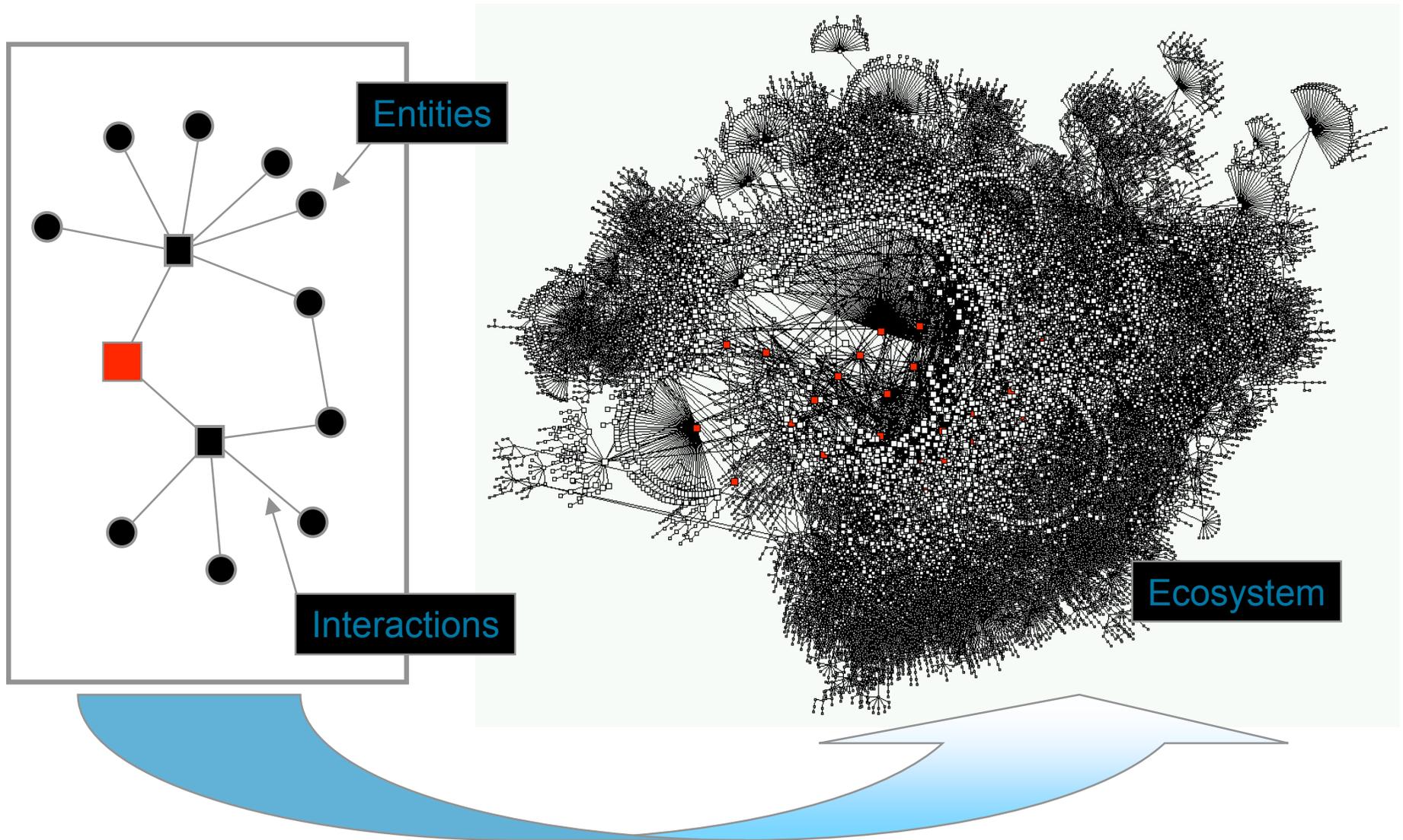
Creation of a Scale-free Network (Barabasi)



Internet Map
February 6, 2003
(Barabasi & Bonabeau, Scientific American May 2003)



Network Definition (IcoSystems)



Individual Actions lead to Complex Ecosystem

Lexical Networks

(<http://visualthesaurus.com>)

Biological Chemistry Example of Scale-Free Behavior

Barabasi, 2002

***The protein-protein interaction network of yeast also has a scale-free topology:
a few proteins interact with a large number of other proteins, while most proteins have only
one or two links.***

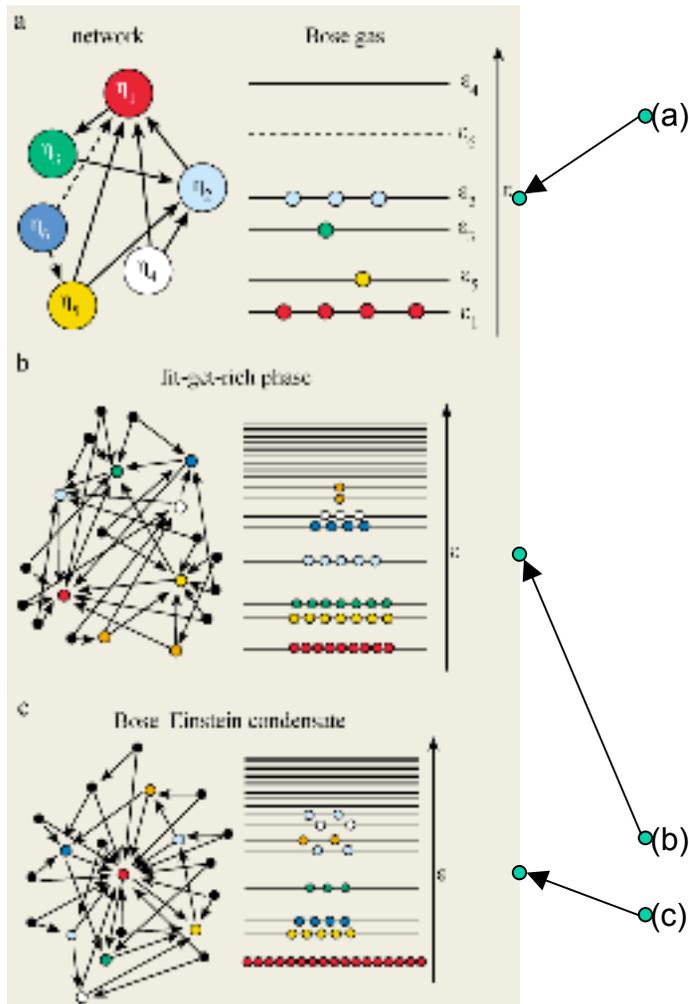


Bose-Einstein Condensate

Example of Fitness-Based, Scale Free Network Dynamics

Barabasi, 2002

A schematic illustration of the mapping between the scale-free model with fitness and a Bose gas.



In the network each node is characterized by a randomly selected fitness, η_i , shown by the different colours. The **fitness** describes the node's ability to compete for links with other nodes η_i the fittest are more likely to acquire more links as the network grows. We assign the energy ϵ_i to each node with fitness η_i using $\epsilon_i = \exp(\beta \eta_i)$ to obtain a **Bose gas with random energy levels**. In the mapping, the fittest nodes (high η_i) result in the lowest energy levels (small ϵ_i). A link from node i to node j in the network corresponds to a particle in level ϵ_j in the Bose gas. The network evolves over time by adding a new node (η_6) that connects to two other nodes (dashed lines). In the Bose gas this corresponds to the addition of a new unoccupied energy level (ϵ_6 , dashed), and the deposition of two new particles in ϵ_1 and ϵ_5 , the energy levels to which η_6 connects. As the network grows, the number of energy levels and particles increase linearly in time. The calculations show that, depending on the shape of the distribution from which the energy levels (fitnesses) are selected, two distinct phases can develop:

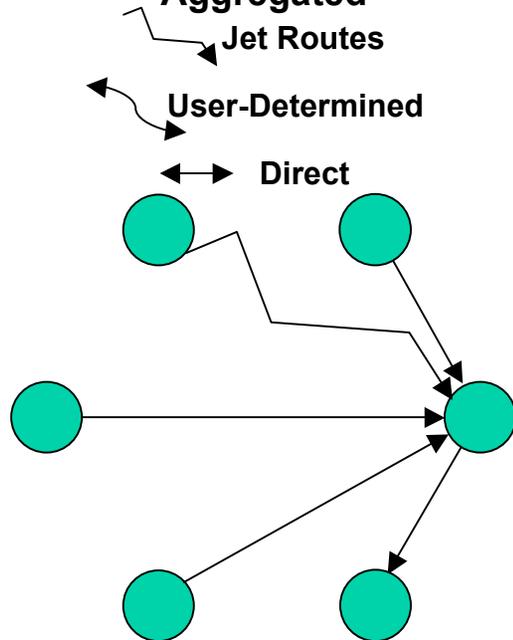
In the **"fit-get-rich"** phase there is no clear winner. The particle density decreases as the energy level increases.

In contrast, when **Bose-Einstein condensation** takes place, the fittest node attracts a significant fraction of all links. This node appears as a highly populated, lowest energy level while higher energies remain only sparsely populated.

Air Transportation Topologies & Lexicon (proposed)

Physical Layer for Three Air Transportation Networks

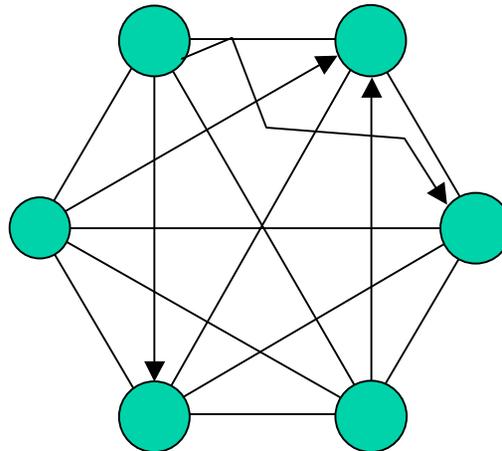
A. Hub-and-Spoke
Directed, Scheduled,
Aggregated



Nodes (n) = 6
Links (k) = n-1 = 5

For Example:
ORF- ORD:ORD- DEN
RIC - MSP: MSP - GFK
Tier 1,2 Carriers

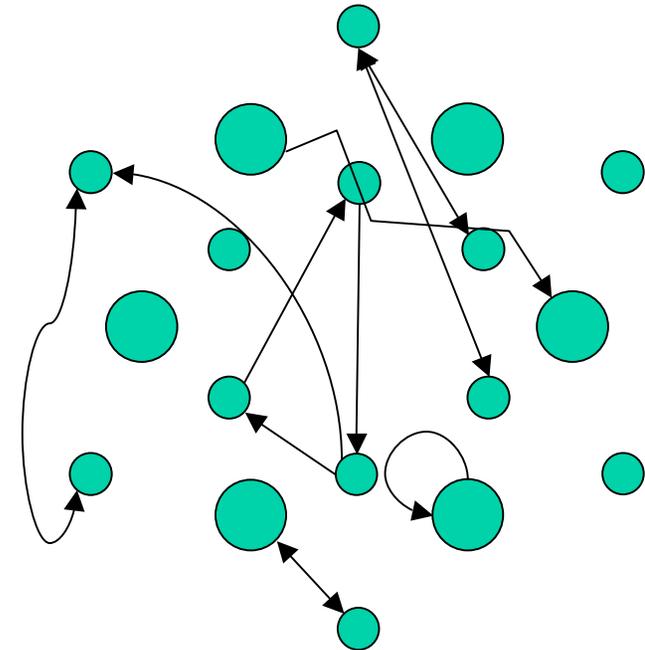
B. Point-to-Point
Directed, Scheduled,
Aggregated



Nodes (n) = 6
Links (k) = n(n-1)/2 = 15

For Example:
ORF- LAS
MDW - NWK
Tier 2,3 Carriers

C. Distributed
Undirected, On-Demand
Dis-Aggregated

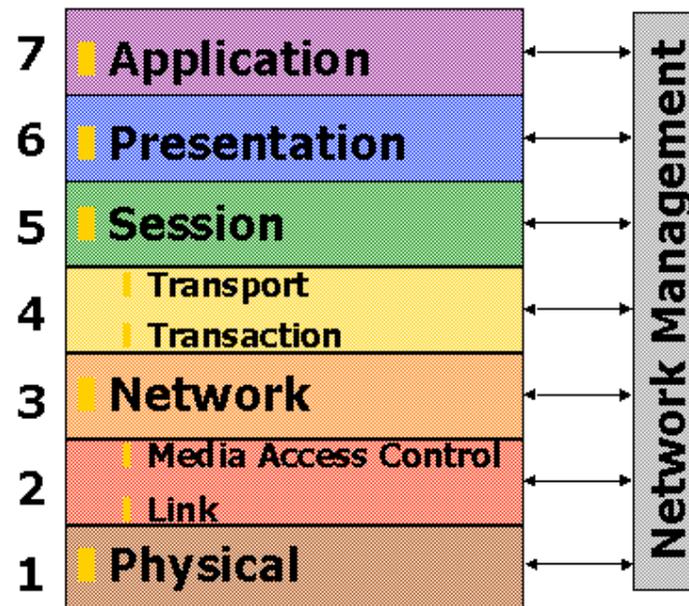


Nodes (n) = 18
Links (k) = n(n-1)/2 = 153
(Three times the nodes = 10X links)

For Example:
PHF - CMH - PHF
JGG - DAN - HEF - JGG
PHF - IAD
JGG - JGG
Tier 4 Carriers, UAVs, RIAs, PAVs

ISO (or OSI) Stack Analogy

LonTalk ISO-Model Protocol Stack

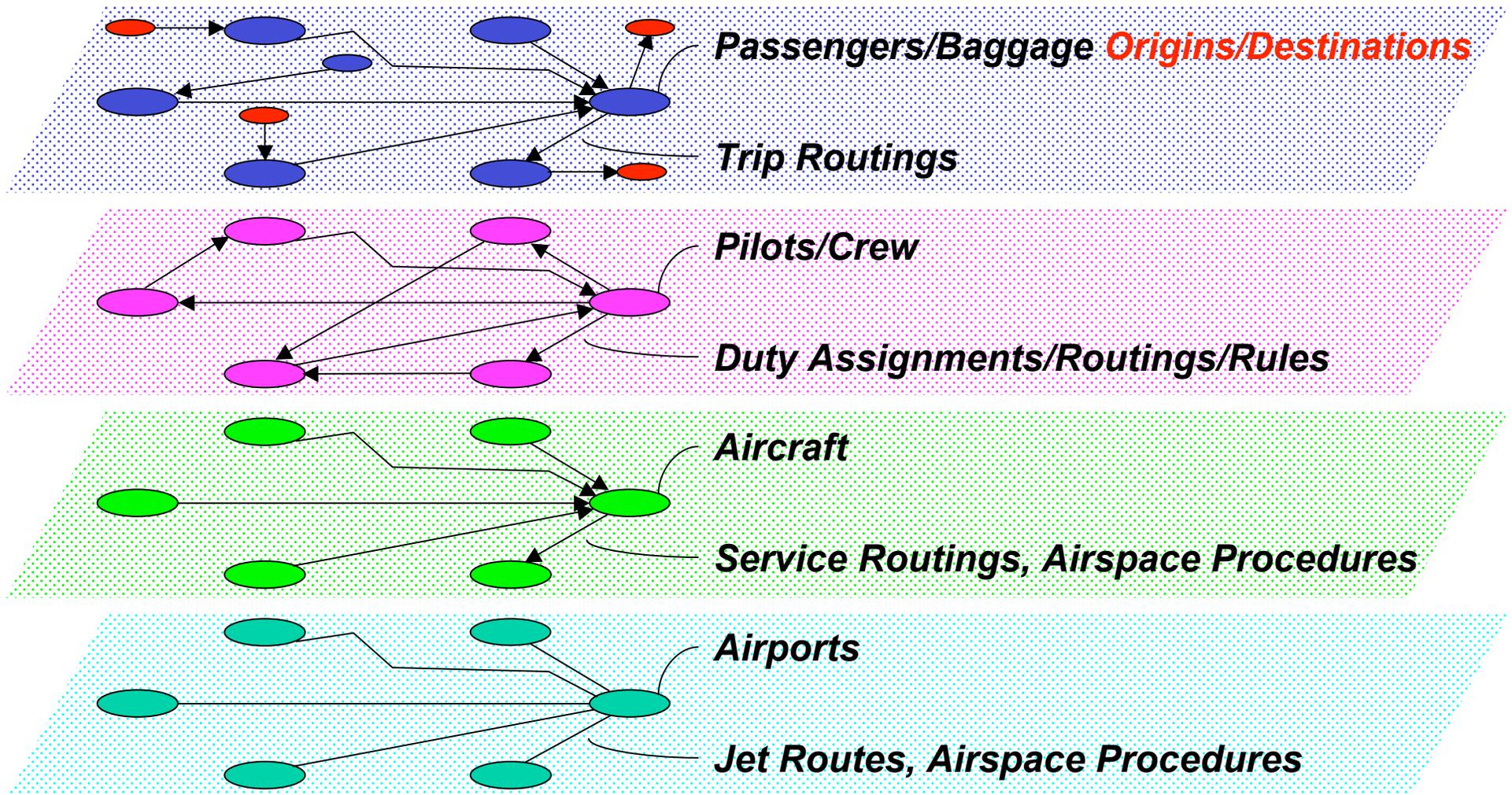


10

© TOSHIBA

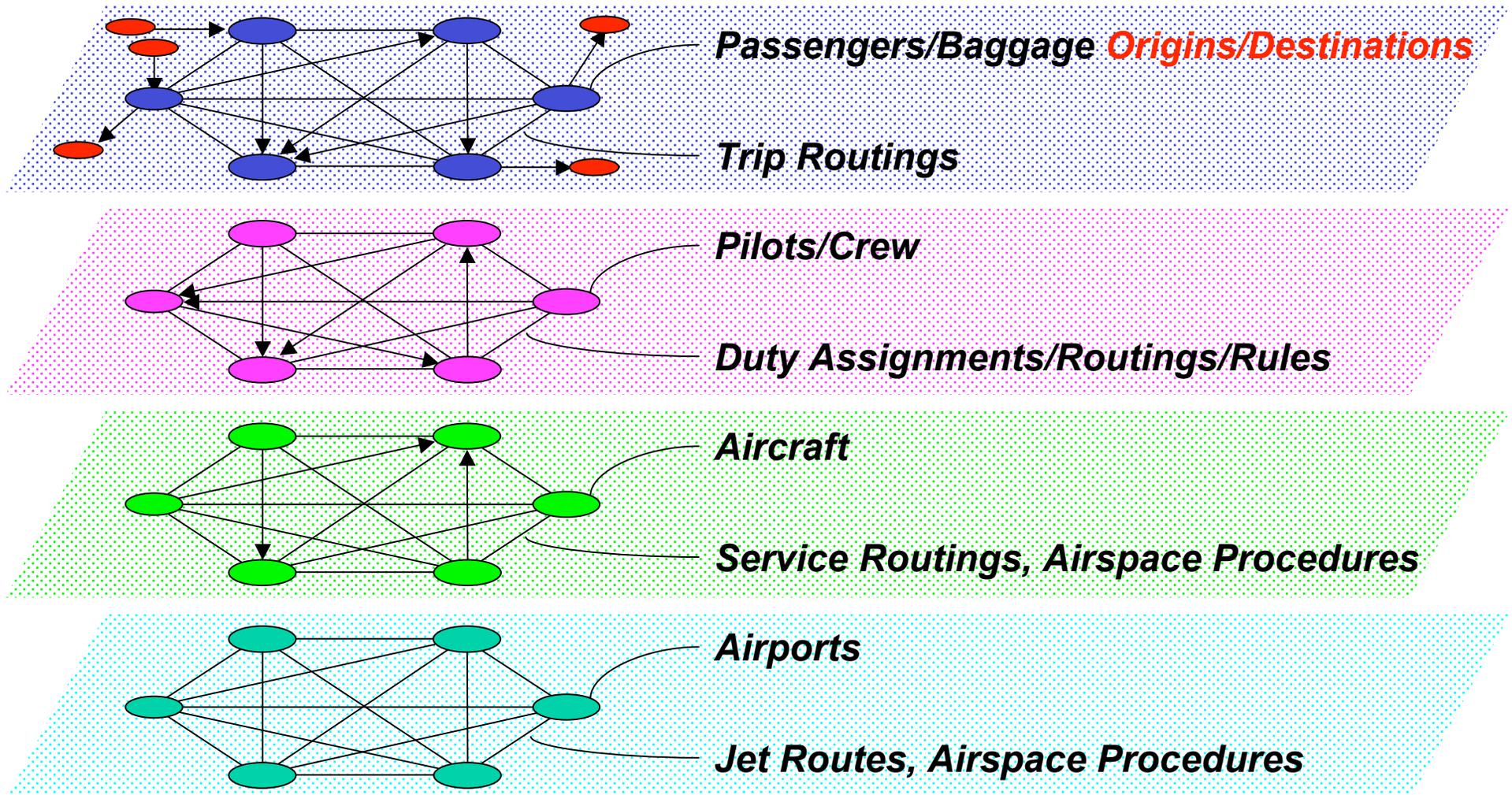
Layered Topology in Air Transportation Network Business Stack

Hub-Spoke, Directed, Scheduled, Aggregated Example



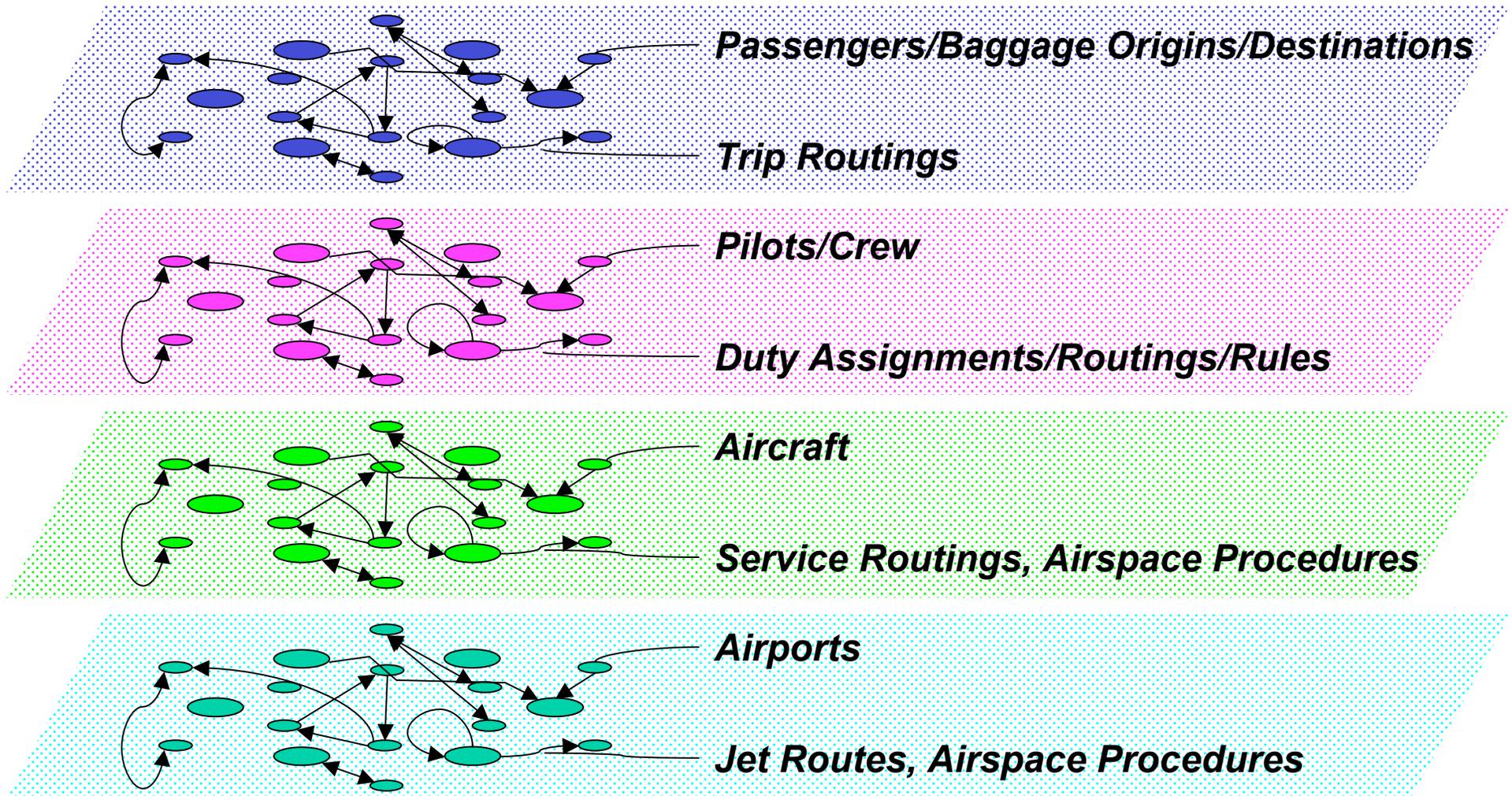
Layered Topologies in Air Transportation Network Business Stack

Point-to-Point, Directed, Scheduled, Aggregated Example



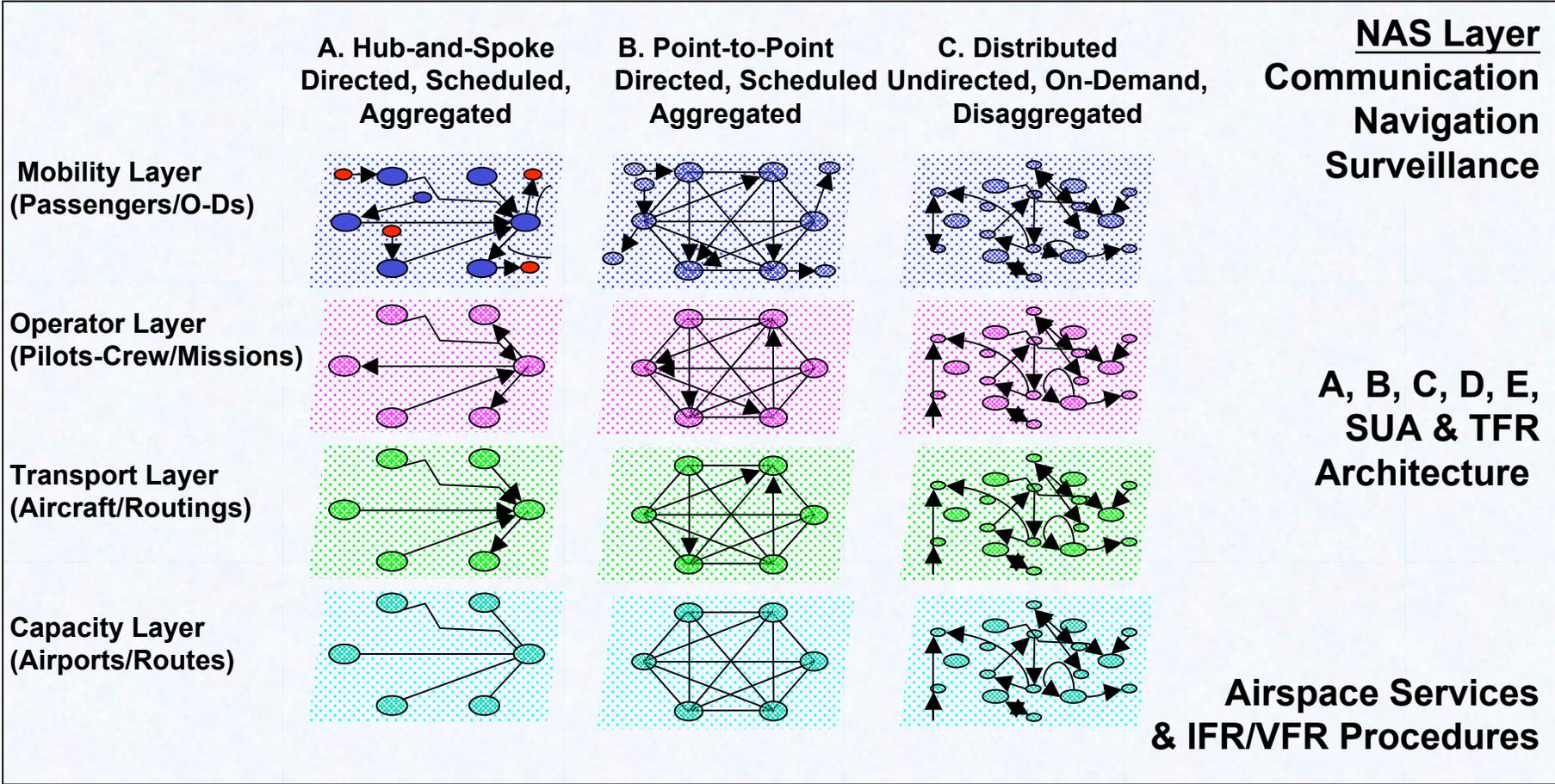
Layered Topologies in Air Transportation Network Business Stack

Distributed, Undirected, On-Demand, Dis-Aggregated Example



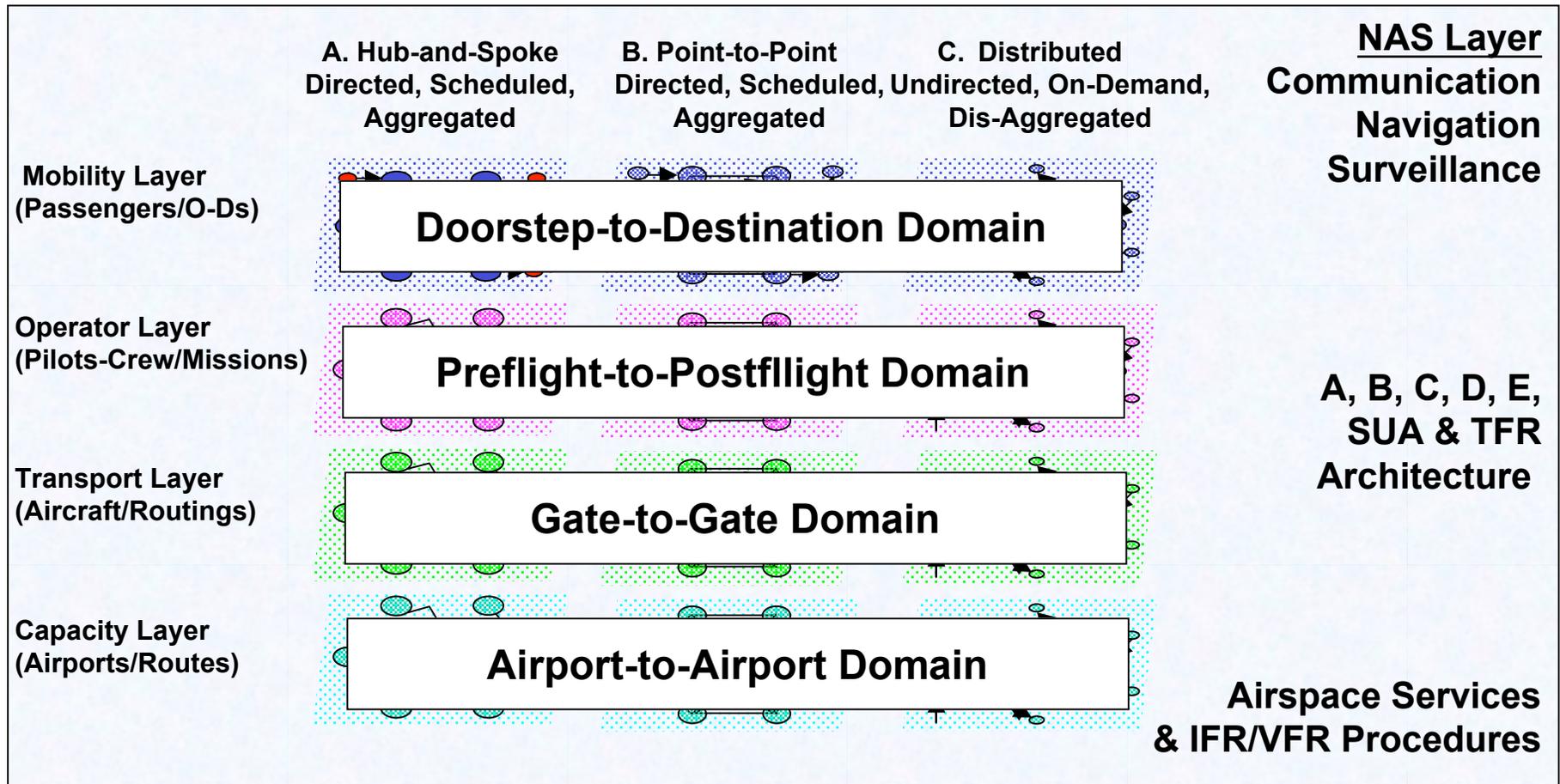
Proposed Topology for Air Transportation Networks

Q: What network characteristics, topologies, and technology strategies would lead to scalable air transportation system behavior?



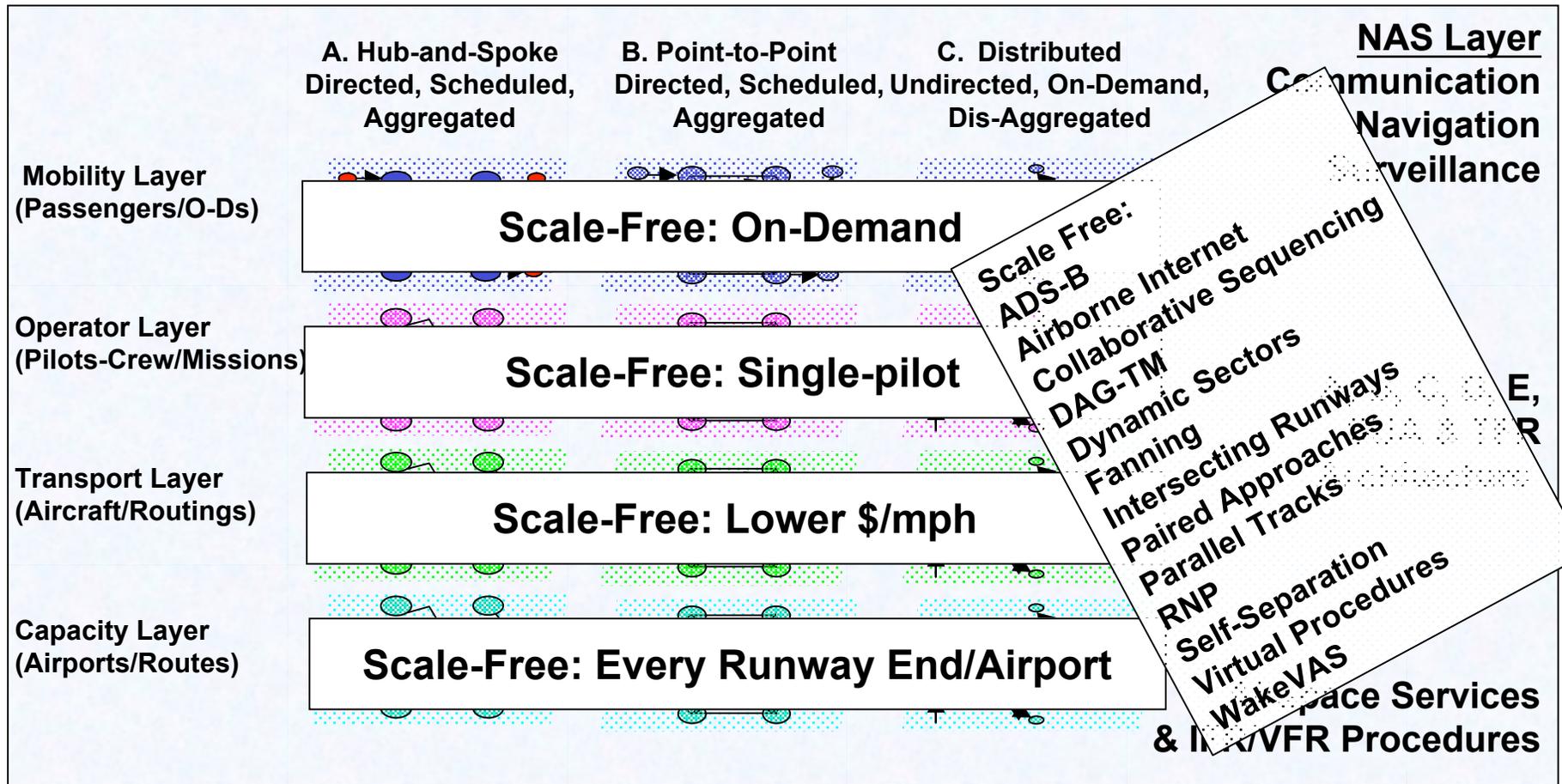
Domain Layers for Air Transportation Networks

Q: What network characteristics, topologies, and technology strategies would lead to scalable air transportation system behavior?

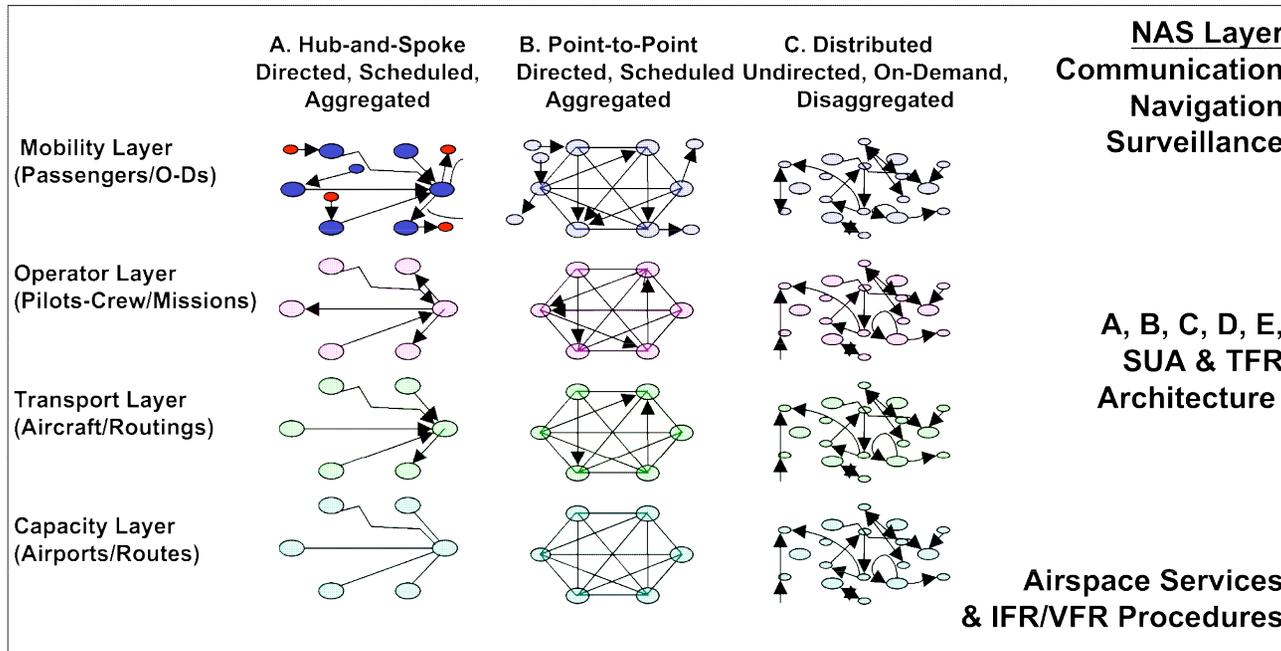


Scalability in Layers for Air Transportation Networks

Q: What network characteristics, topologies, and technology strategies would lead to scalable air transportation system behavior?



Proposed Topology for Air Transportation Networks



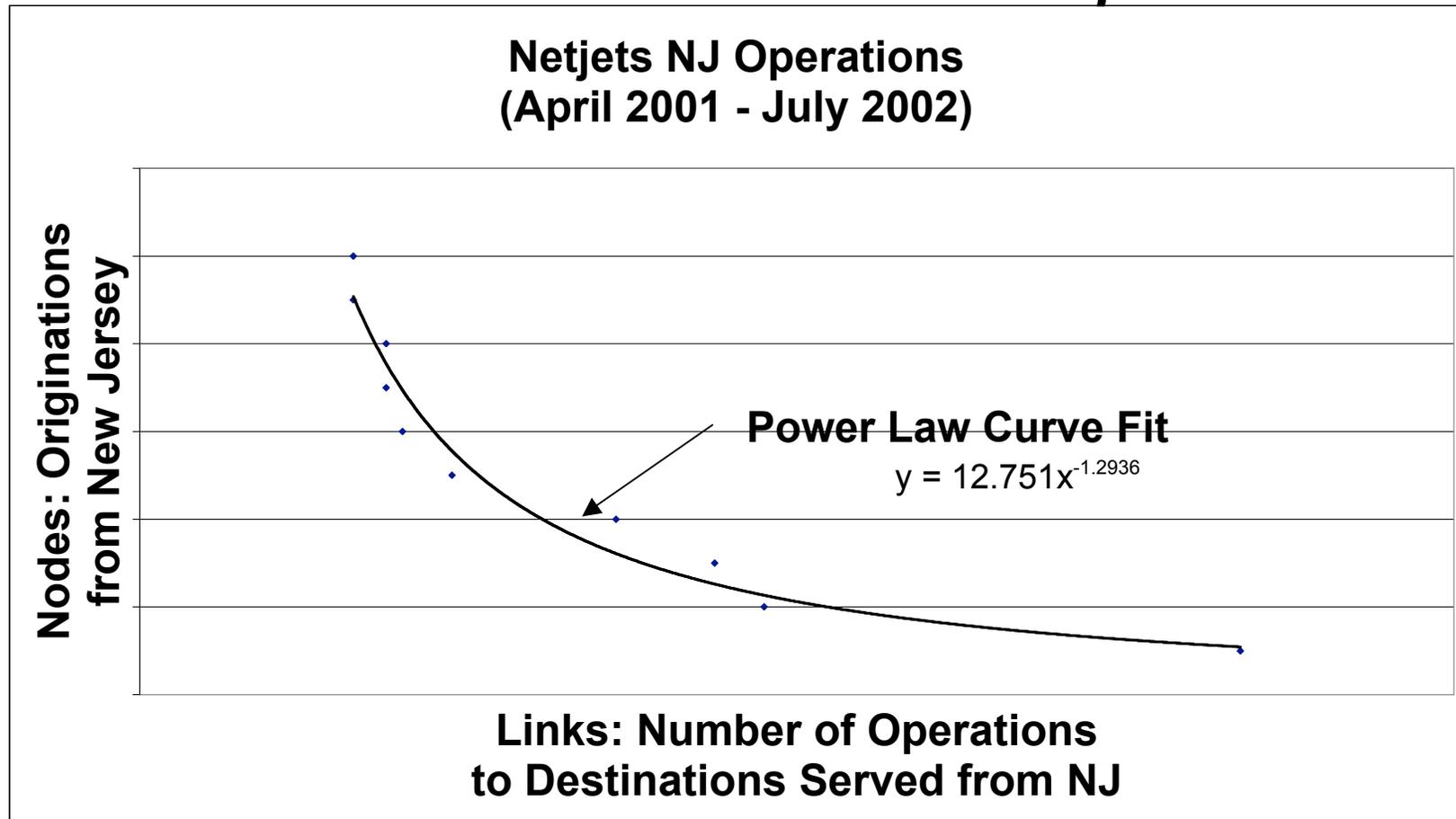
Look Complex?... IT IS!

However, the implications of scale-free (or small world) theory are that understanding of global network dynamics (including self-constituting and emergent behaviors) may be approachable through simulations of simplified local elements of the network.

So, how's this different that what we do now?

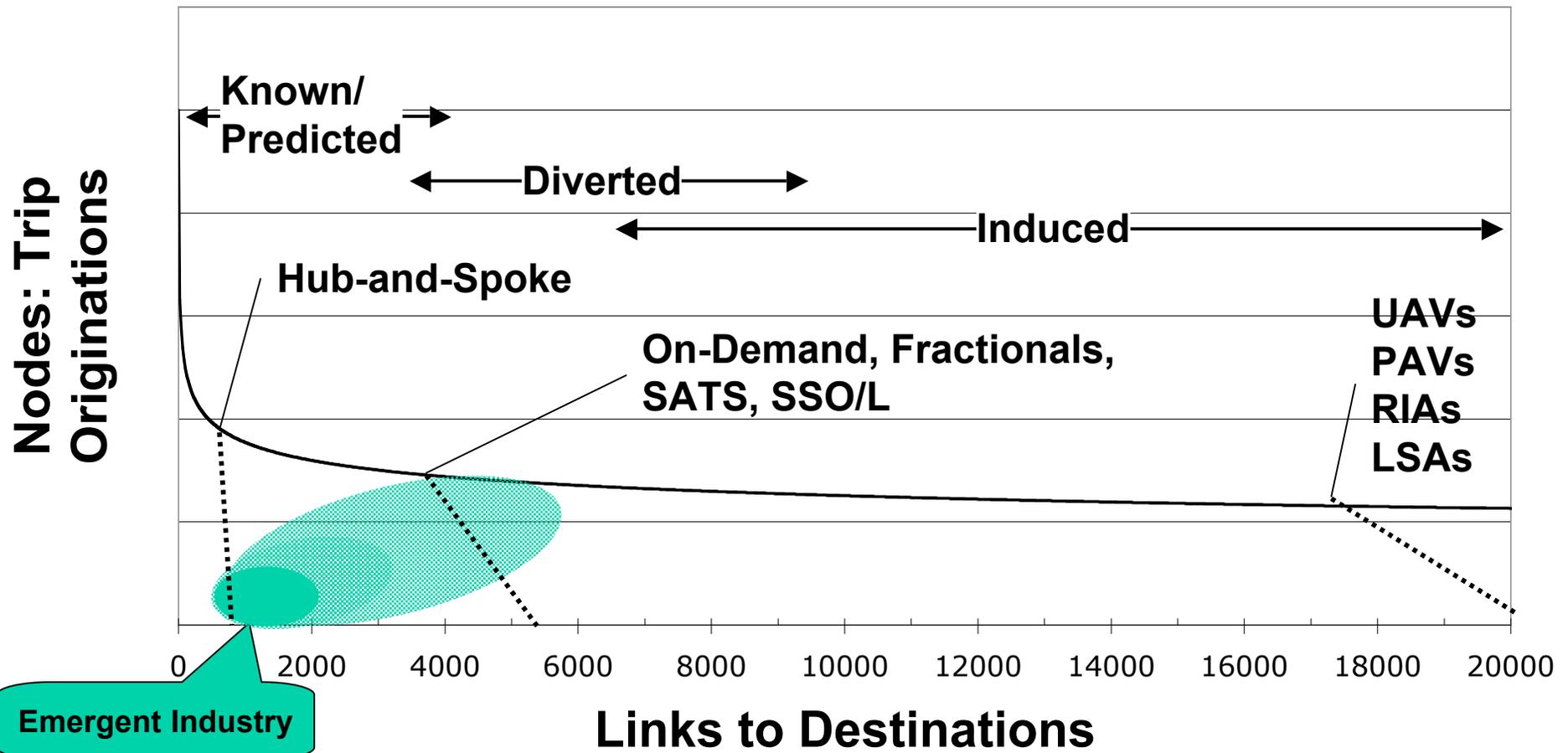
Our current understandings and analytical approaches to airspace & vehicle architectures are largely based on deterministic systems (e.g., networks A and B above), and do not readily apply to non-deterministic, scale-free networks (e.g., network C above). Yet the concept of operations for a future NAS that supports distributed operations of UAV, RIA, PAV, and alternative subsonic vehicle concepts appears to require understanding of scale-free network behaviors.

Scale-Free Distribution of NetJets Operations



- The links (operations) from a few of NetJet's nodes in NJ to their top ten destinations from NJ nodes (originations) follow a power law distribution.
- For NetJets, this distribution of nodes with links extends out to about 1250 airports annually.

Power Law Distribution in Air Transportation (Physical & Transport Layers)

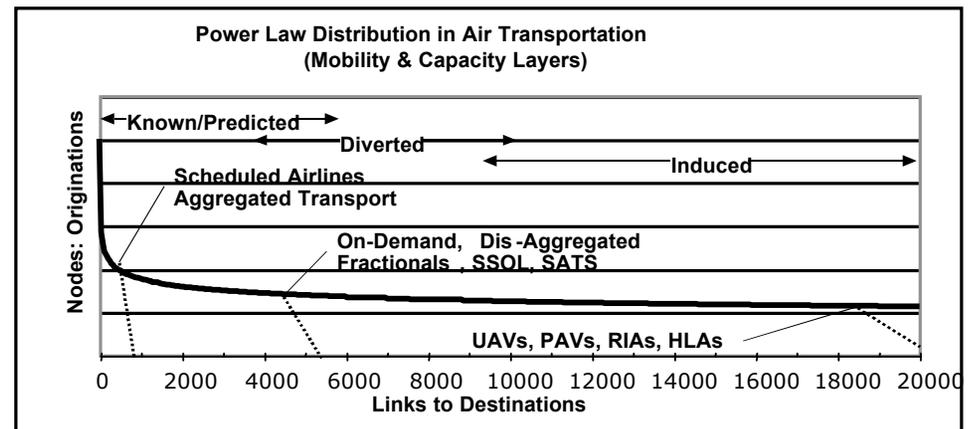
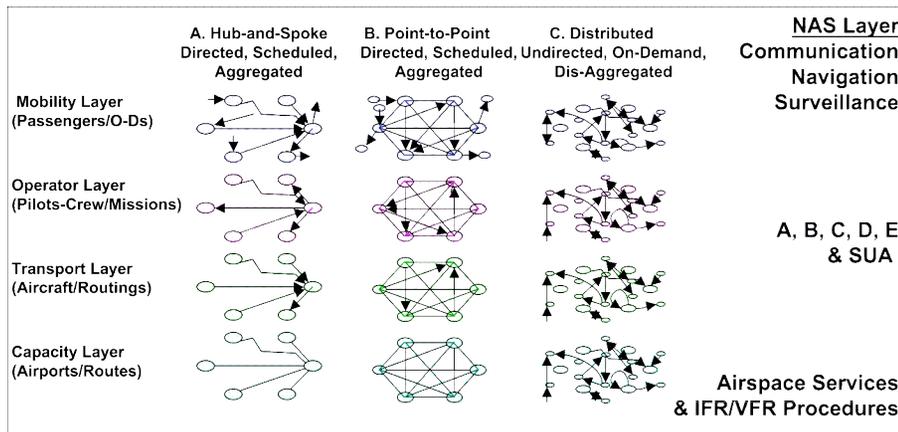


Examples of Scalable Behaviors in Air Transportation Topology

- Physical layer (airports-infrastructure) supports growing access to more runways in more weather
- Transport layer (new aircraft) supports growing access to more markets/communities
- NAS layer (airspace architecture & procedures) supports ubiquitous airspace access and services

Air Transportation Topology

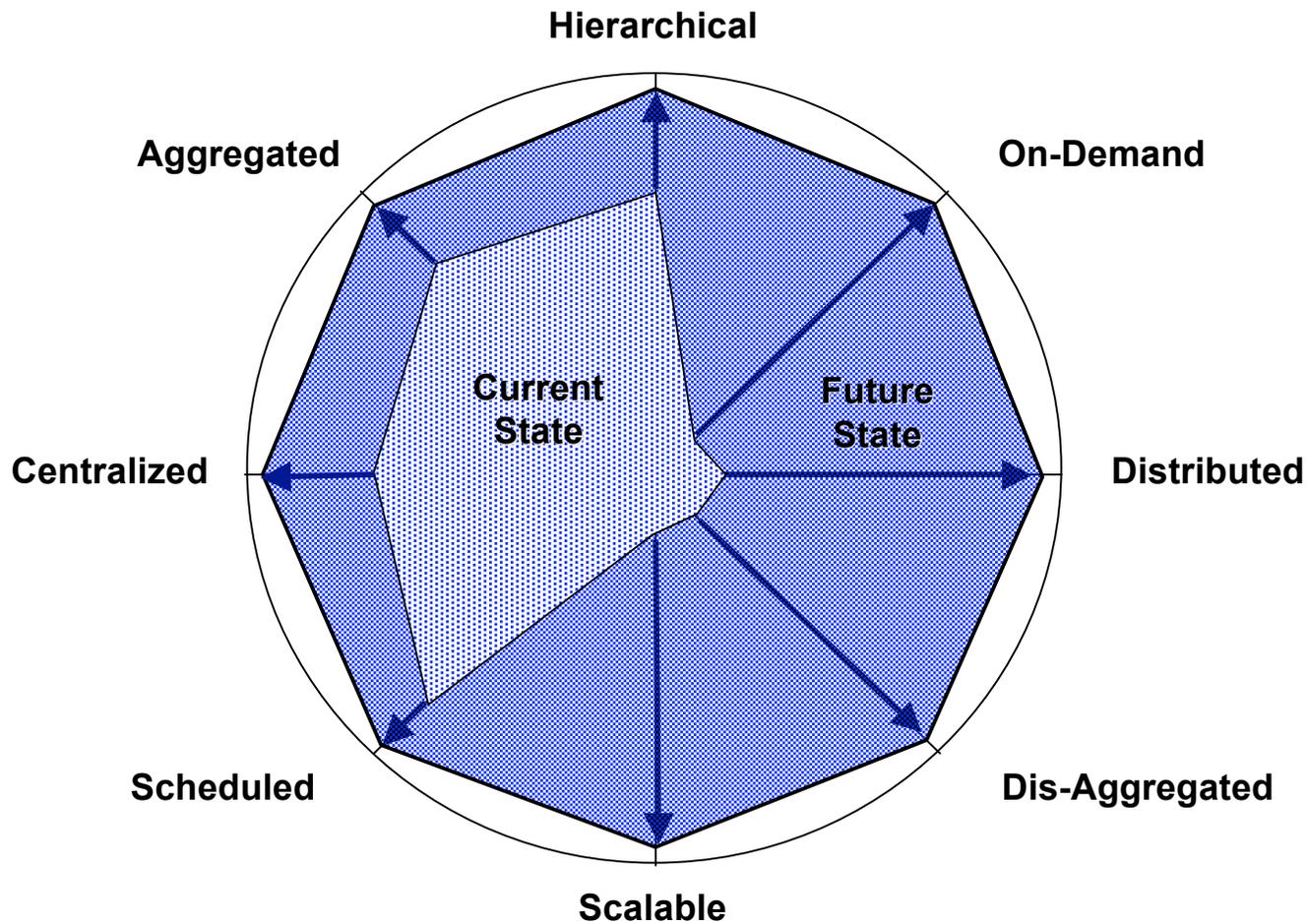
As framework for primal questions



Primal Questions

1. What are the comparative mobility metrics (e.g., door-to-door speeds) for networks A, B, and C?
2. What are the optimal sizes, costs, performance of aircraft for these networks?
3. What are the comparative energy consumptions for optimized operations of these networks?
4. What are the comparative noise constraint optimization issues for these networks?
5. What are the comparative infrastructure costs at each layer of these networks?
6. What are the comparative degrees of resistance to disruptions of these networks?
7. What are the comparative degrees of vulnerabilities of these networks?
8. What are the percolation behaviors for “events” in these networks?
9. What changes occur within the network when one of the layers is fundamentally altered?
10. What topology of topologies (system of systems) expands the transformation concept space?

Transformation Concept Space (Notional)



The vision is to expand the concept space along *all* dimensions.

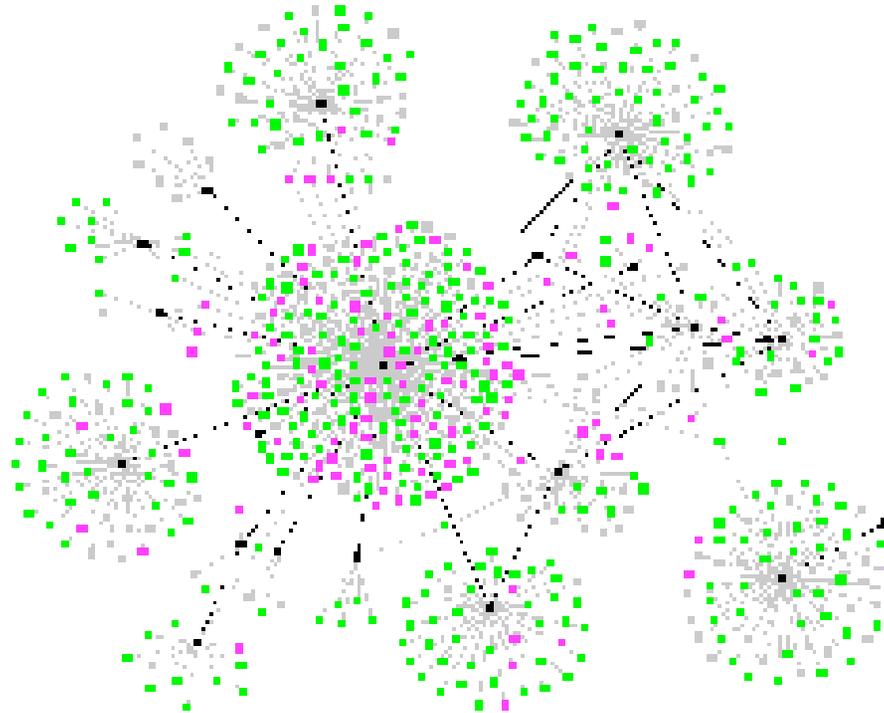
Percolation, Diffusion, Cascading

Network Diffusion/Percolation

Barabasi, 2002

The spread of viruses in scale-free networks is aided by hubs-- once a hub gets a virus, it can pass it on to a very large number of nodes.

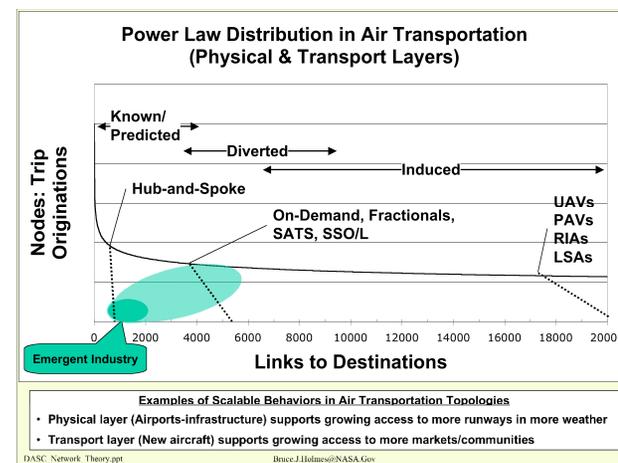
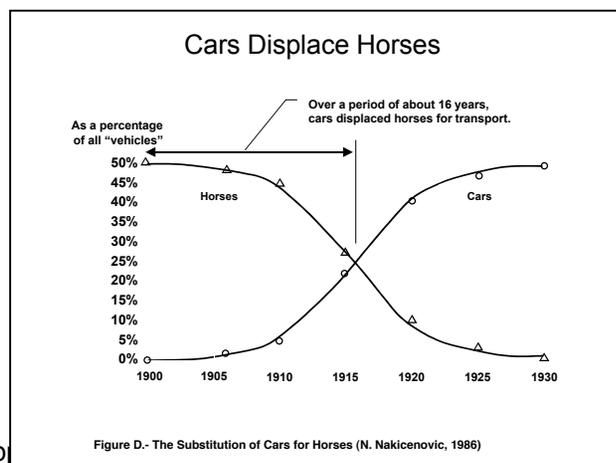
(from <http://www.orgnet.com/contagion.html>)



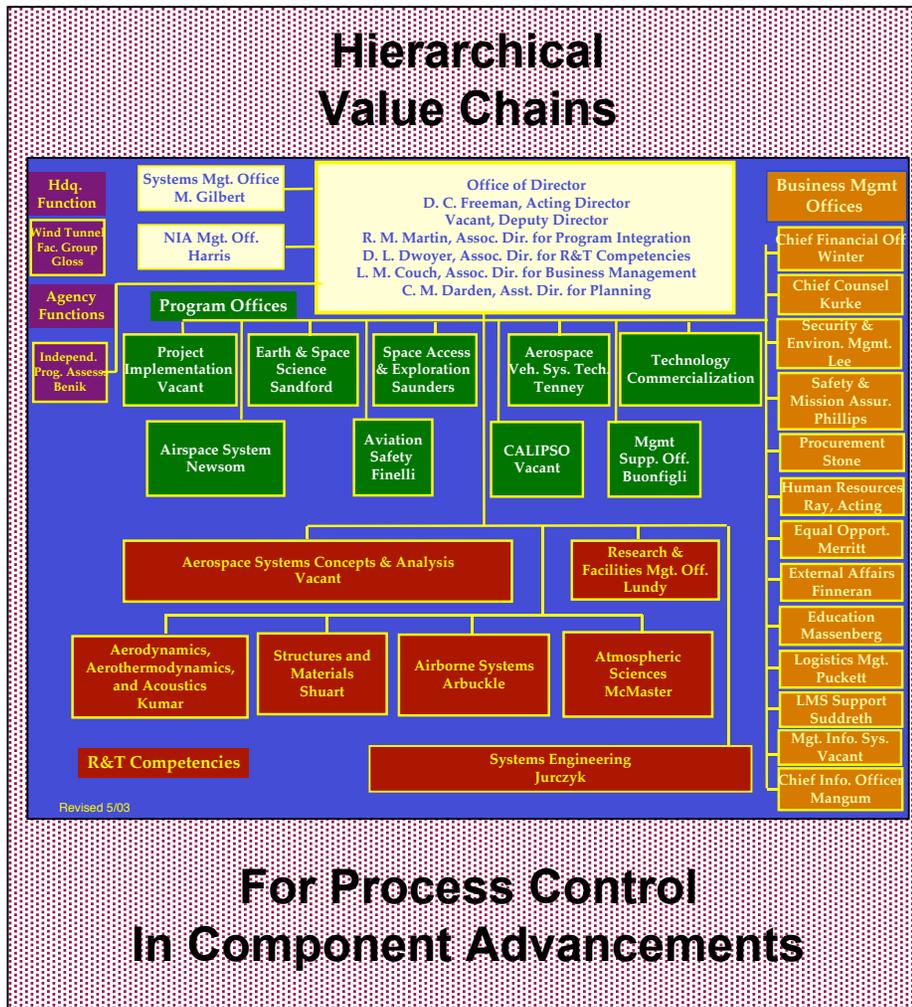
Network Diffusion/Percolation

Role in Innovation Life Cycles

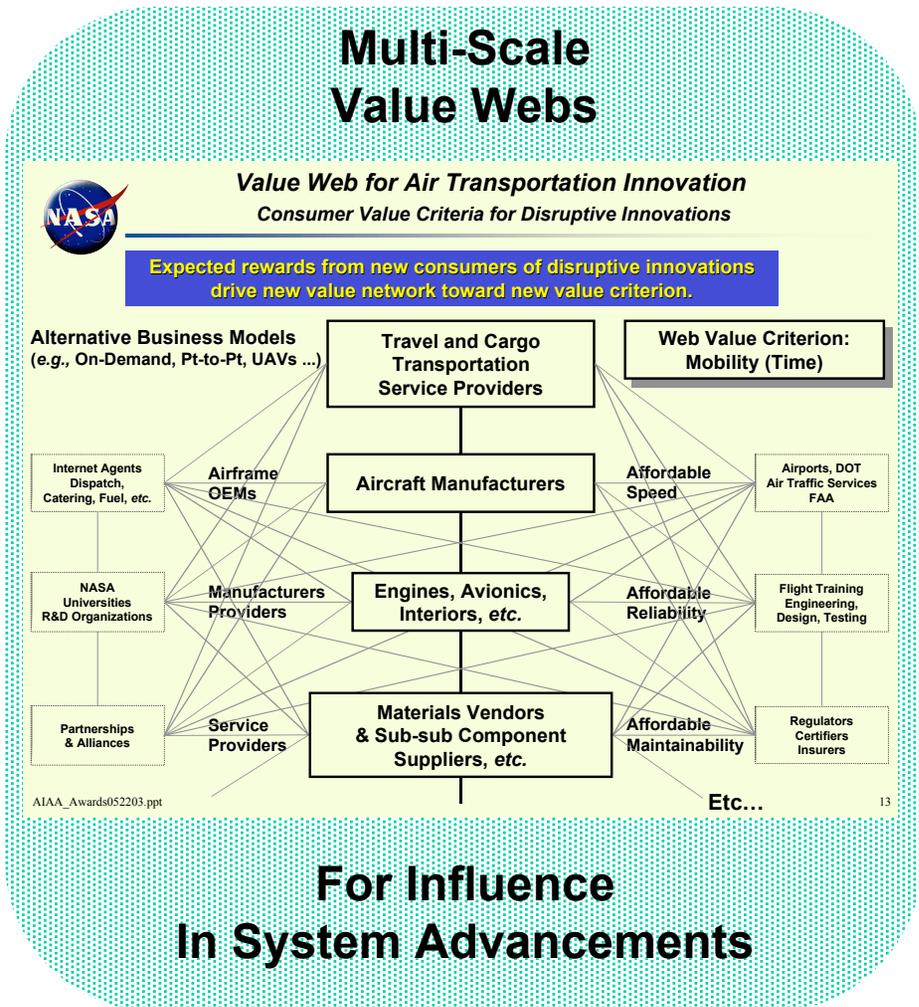
- Innovation life cycles are shaped by network behaviors
- Rates of diffusion are functions of:
 - Scale free nature of the network (growth by preferential attachment)
 - Thresholds of vulnerability (existence of need)
 - Existence of a well-connected percolating cluster (incubator for innovation)
 - Distribution of early adopters (potential for growth of links)
 - The size of the clusters of early adopters (existence of highly linked groups)
 - Links between early adopters and innovators (ability to legitimize the innovation)
- These conditions enable global cascades to occur. Global cascades exhibit self-perpetuating growth, ultimately altering the state of the entire system.



Organizational Architectures



Hierarchical networks perform weakly in conditions of ambiguity, uncertainty, disruption.



Multi-scale networks perform strongly in conditions of ambiguity, uncertainty, disruption.

Synergy with Object-Oriented Technology? (Is there a Nexus Here?)

- **Object Technology appears to offer an approach to software deployment that appears highly relevant to scale-free network behaviors.**
- **Object classes and subclasses appear to have analogs within the layers of network topologies.**
- **Both Object Technology and Scale-Free networks exhibit scalability and evolution as characteristics.**
- **Both Object Technology and Network Theory have been used to understand molecular dynamics.**
- **Objects appear to exhibit node-like (network) characteristics.**
- **Object Interfaces appear to exhibit link-like (network) characteristics.**

Also:

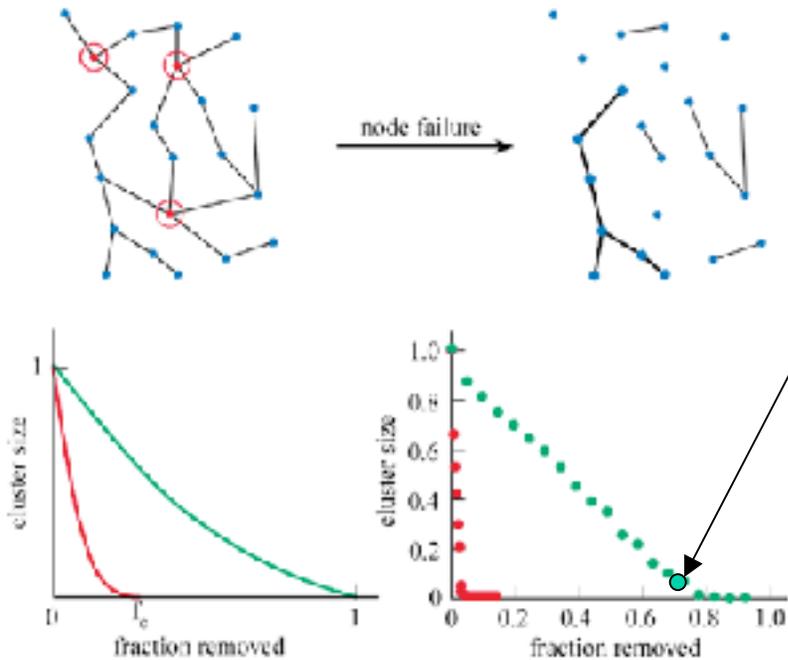
- **What is the relation between Object Technology and Agent-based modeling?**
- **What is the relation between Agent-based modeling and System Dynamics approaches?**

Robustness and Vulnerability

Robustness Analysis

Barabasi, 2002

Random Network —
Scale-Free Network —



The robustness of a complex system against errors and failures can be tested by investigating the effect of removing nodes.

(c) Percolation theory predicts that a random network will break into tiny clusters when a critical fraction, f_c , of nodes is removed. This prediction does not hold for scale-free networks as can be shown by plotting the of size of the largest cluster versus the fraction of nodes removed.

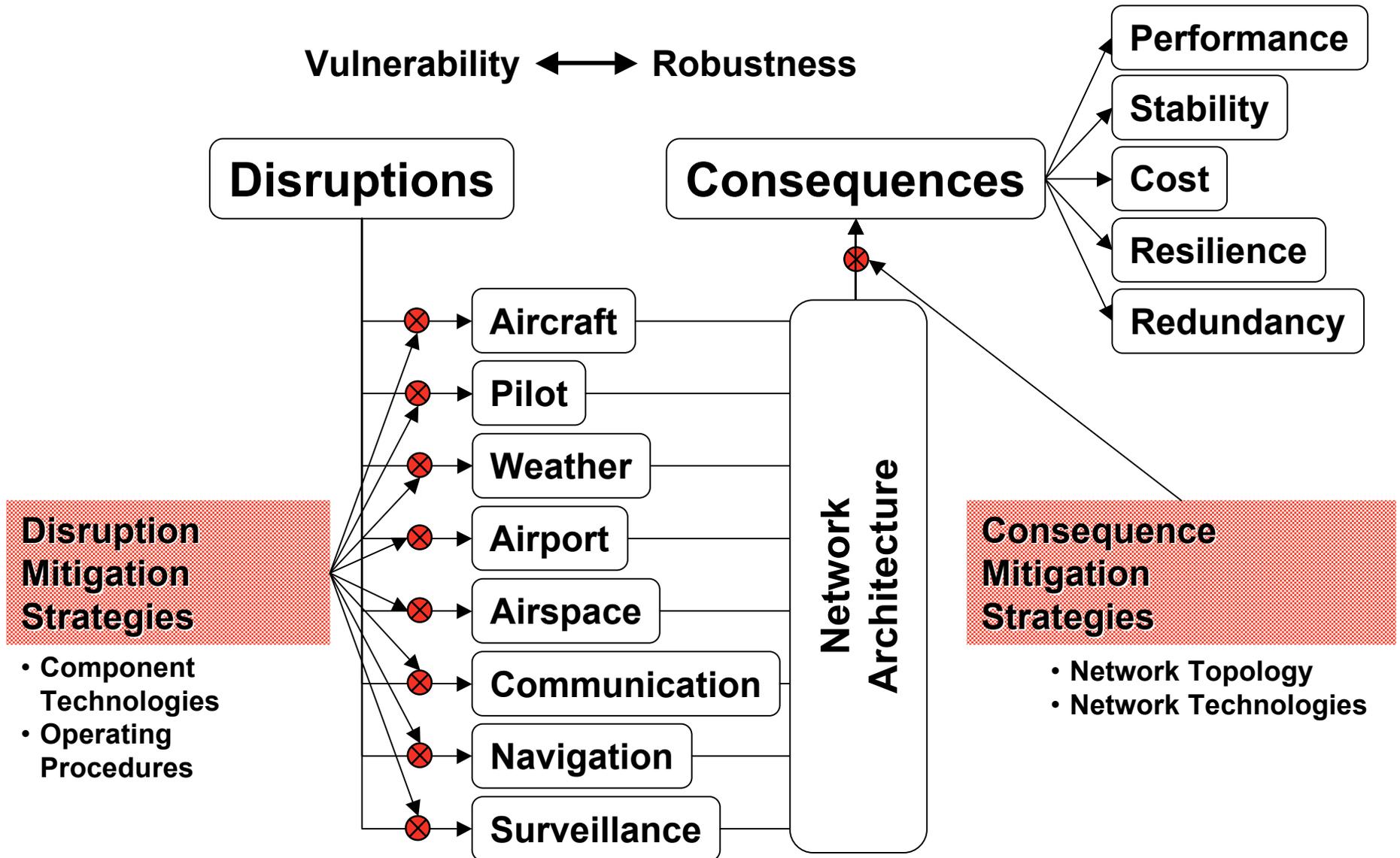
Calculations show that the cluster size only falls to zero when all the nodes have been disconnected (green). However, if the most-connected nodes are removed then the scale-free network will break at a small f_c .

(d) By randomly removing domains from the Internet, we found that more than 80% of the nodes have to fail before the network fragments (green). However, if hackers targeted the most connected nodes (red), then they could achieve the same effect by removing a small fraction of the nodes.

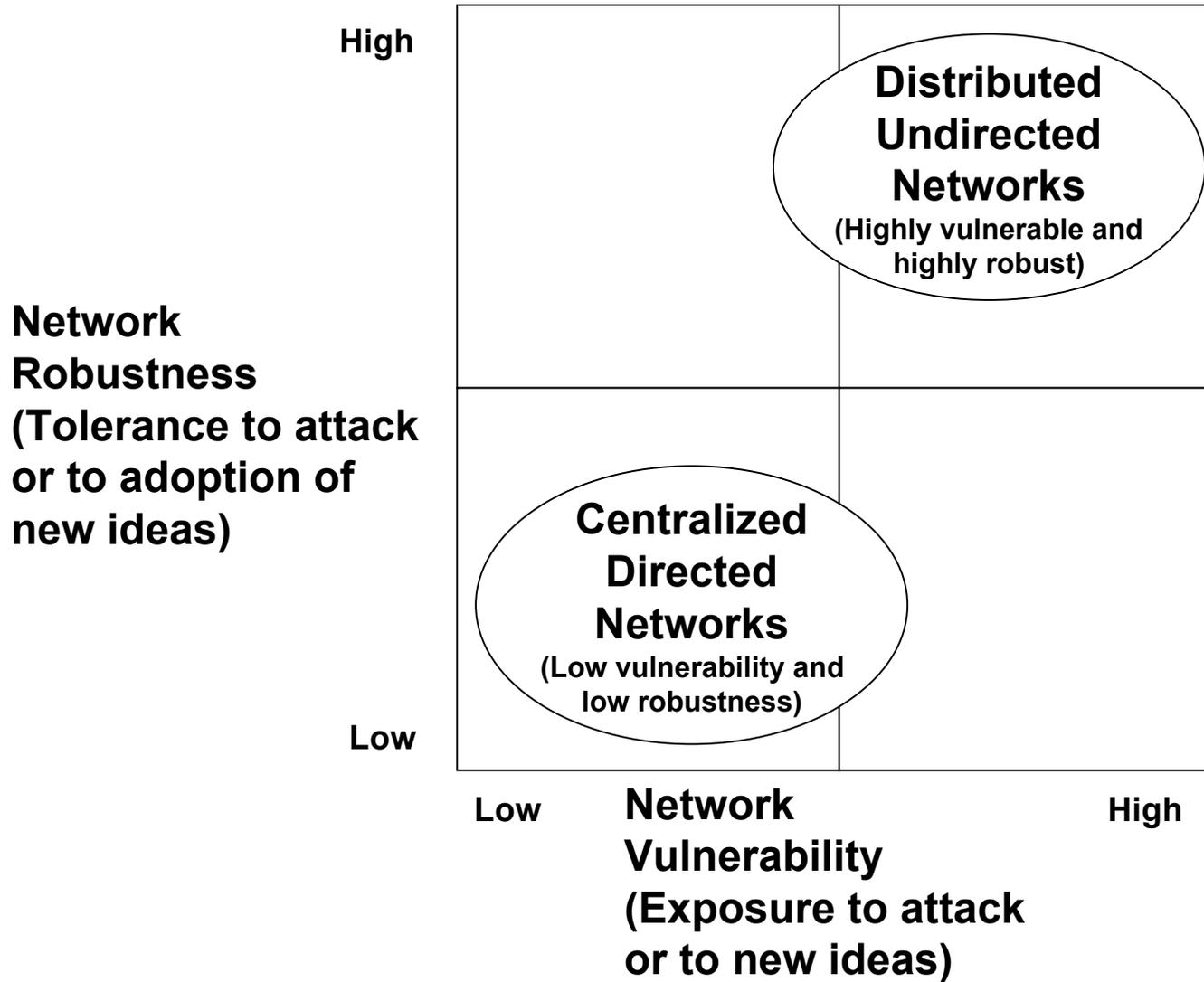
(from <http://www.physicsweb.org/box/world/14/7/9/pw1407094>)

Air Transportation System Network Architecture

Effects on System Stability



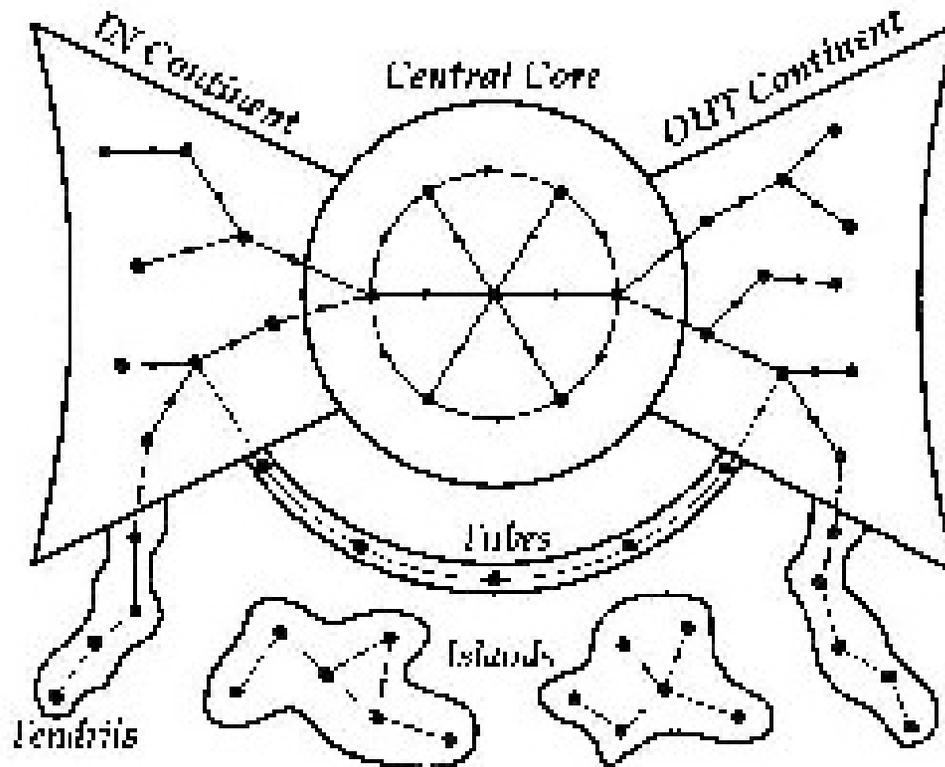
Topological Robustness



Network Topologies

The Continents of a Directed Networks Example of Network Non-Homogeneity

Barabasi, 2002



What is the related architecture for an Airborne Mobile Internet?

Network Performance and Optimization Considerations

Air Transportation Network Applications: Exploratory Questions

- **What network features in air transportation system topologies lend themselves to scalability of the mobility layer? What are the tradeoffs against the other layers (capacity, transport, operation)?**
- **What other transportation system topologies might be appropriate for study?**
 - **A: Subsonic Mega-lifters: Hub-and-Regional, Directed, Scheduled**
 - **B: RIA: Point-to-Point, Directed Scheduled**
 - **C: UAV: Point-to-Point, Undirected, On-Demand**
 - **D: Hybrids, others?**
 - **E: Altered CNS, airspace architectures and procedures**
- **What are the implications of scale-free network performance on vehicle system technologies (distributed sensing, computing, controlling; automation; autonomy)?**
- **What might comprise hubbing behavior in an on-demand, point-to-point network?**
- **What network performance parameters would make sense for the quantification of air transportation network vulnerability, resilience, robustness, and redundancy?**
- **What are the implications of fitness-based, scale-free network performance on airspace architectures and technologies (Airborne Internet, Distributed Decision-making, dynamic TerPs, dynamic sectors)?**
- **Since all complex systems have vulnerabilities, what combinations of complex systems of individual topologies might create desired behaviors (increased robustness, performance)?**
- **How can an air transportation system network models be validated?**

Workshop Planning (Notional)

- **Workshop on network theory, tools, and applications in air transportation networks**
 - **Purpose: Produce a roadmap between theory and applications of network theory to air transportation networks. Produce a set of problem statements, a lexicon, and assessments of readiness of tools for problem solving.**
- **Participants:**
 - **NASA**
 - **NIA**
 - **Academia**
 - **Industry**
- **Outcomes:**
 - **Propose lexicon for air transportation systems**
 - **Propose a topology**
 - **Determine level of readiness for computations in specific applications of the theory**
 - **Determine what is still at the theoretical stage**
 - **Identify key participants in future exploration**

Summary

- **Science of networks appears to offer a framework for:**
 - Ways of thinking about complex systems that could affect technology strategies, public policies, business strategies, etc. for aeronautics programs
 - Ways of analyzing simplified models of network architectures to assess alternative strategies, high level architectures, and comparative performance.
- **A notional air transportation network topology is proposed**
 - **Lexicon: Capacity Layer; Transport Layer; Operation Layer; Mobility Layer, Disturbance Layer, CNS Layer, ...**
 - **Air transportation architecture assessments should include evaluation of future airspace/vehicle system architectures with properties of:**
 - Scalability/Demand adaptability in numbers of aircraft operations (separation and sequencing), unconstrained by existing CNS architecture and ATC procedures
 - Negotiated-determinism (un-directedness) in origin and destination landing facilities, independent of existing airport and airway infrastructure (including jet routes, ILS, etc.)
 - Dynamic network behavior in transportation services operating models, including hubbing and non-hubbing and scheduled and on-demand systems
 - Others...
- **Next steps:**
 - **Establish a shared lexicon**
 - **Identify architecture of tools and competencies for transportation network modeling**
 - **Establish challenge problems**
 - **Build a roadmap**

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(2) Santa Fe Institute, 1399 Hyde Park Road, New Mexico 87501, USA.
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