Challenges in Design, Implementation and Operation of Heterarchical Controls for Dynamic Logistic Systems

Prof. Neil A. Duffie

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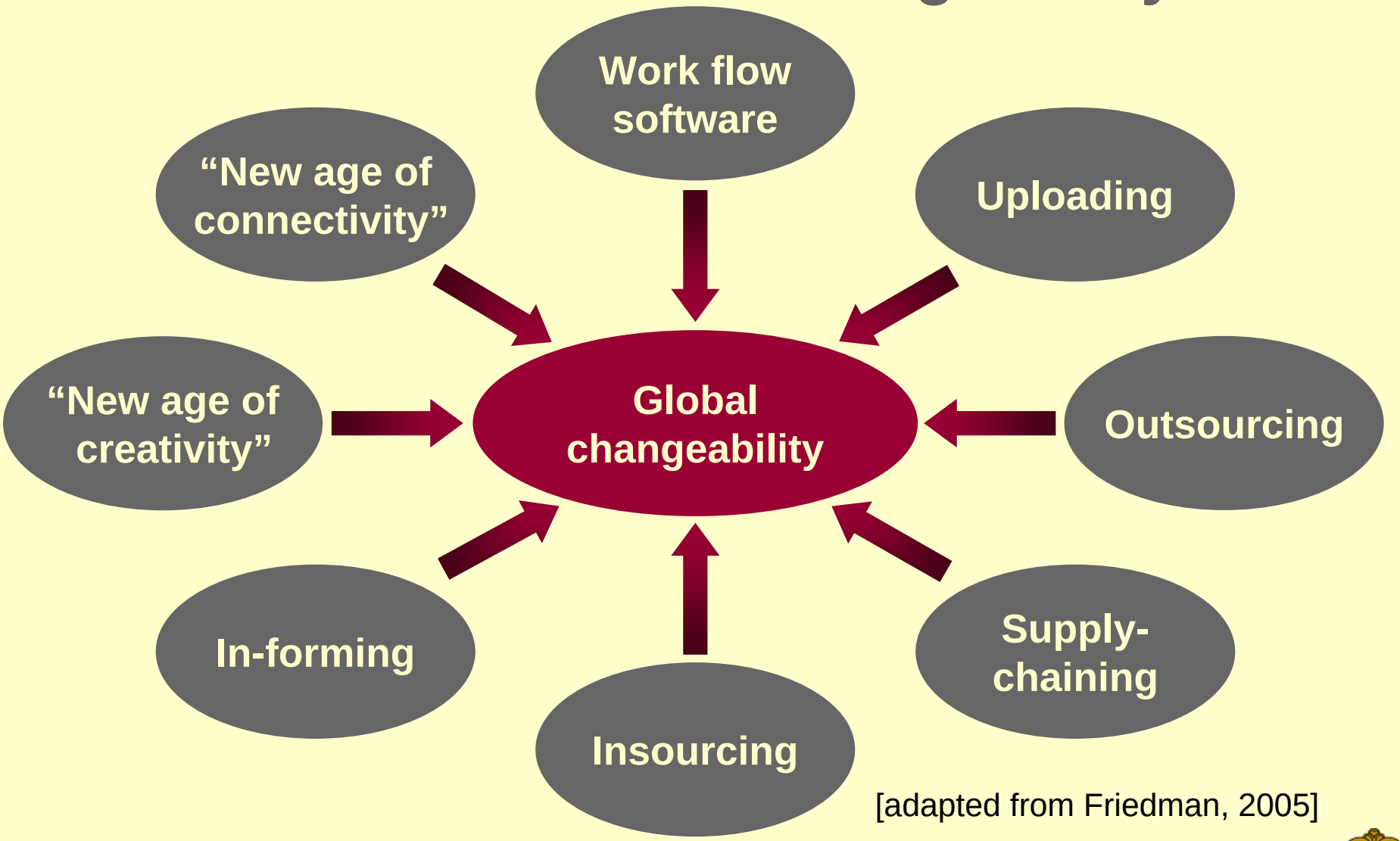
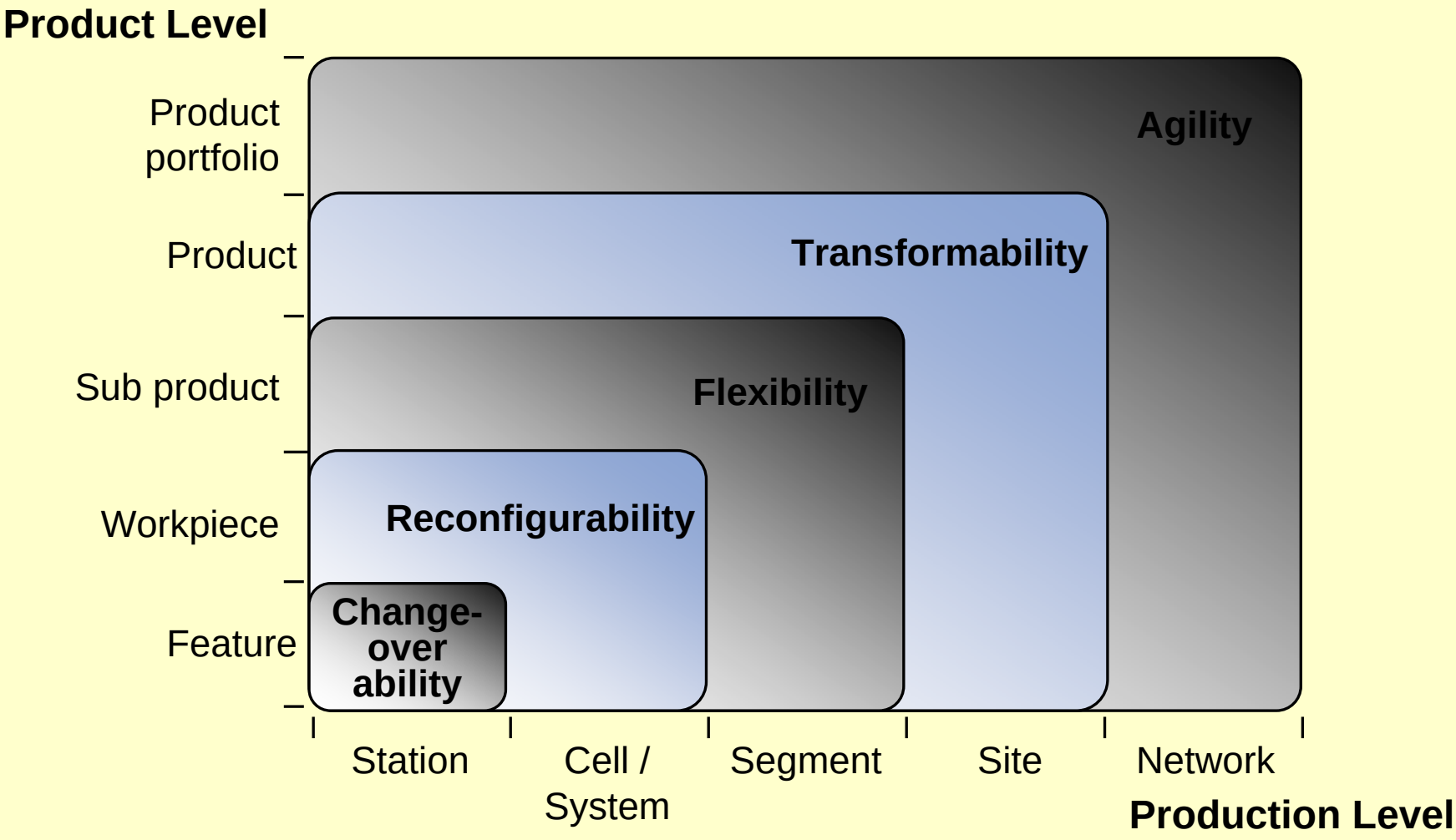
Drivers of Global Changeability



[adapted from Friedman, 2005]

Types of of Production Changeability



[adapted from Wiendahl et al., 2007]

Technologies ⇒ Opportunities

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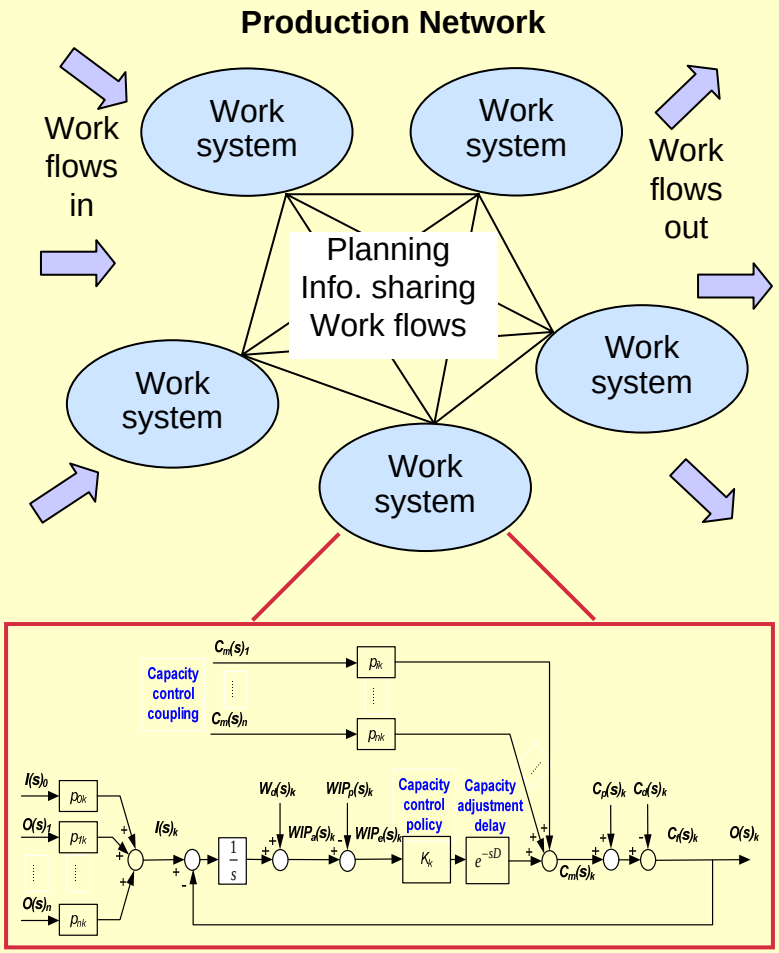
Example: Control-theoretic Modeling

- Motivation
  - Production networks aim to reach a stable state and high logistic performance on a global level in the presence of incomplete information and uncertainty.
  - Is it possible to guarantee stability, robustness and certain logistic performance of a production network with decentralized, autonomously controlled work systems using an analytical approach?
- Preliminary Results
  - Control-theoretic methods were used to model decentralized capacity control in a network of workstations, predicting performance and designing of local autonomous decision rules.
  - Dynamics of decentralized production decision making in response to loss or incomplete sharing of information were analytically modeled, verifying robustness.



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Challenges

- What could/should be the characteristics of designs of future controls for logistic systems?
- From what domains can guidance for design of controls for logistic systems be drawn?
- Which fundamental design philosophies will produce
  - Agile, trustworthy and profitable logistic systems?
  - Systems that can be evolved easily over time?
  - Less “jump off the cliff” system investment?
- What combinations of technologies and methods can be used to
  - Efficiently implement systems designed using such philosophies?
  - Produce favorable dynamic behavior in turbulent conditions?

Focus

- What could/should be the characteristics of designs of future controls for logistic systems?
- From what domains can guidance for design of controls for logistic systems be drawn?
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  - Produce favorable dynamic behavior in turbulent conditions?

Outline

- Options and philosophies for structuring controls for logistic systems
  - Hierarchical, heterarchical, etc.
  - Justification for choice heterarchical structures
- Domains of existing knowledge and examples that can guide design of heterarchical controls:
  - Manufacturing machinery, cell and system control
  - Organizations
  - Web services
- Vision for future controls for logistic systems, their development and their evolution

1. Options for Structuring Controls for Logistic Systems

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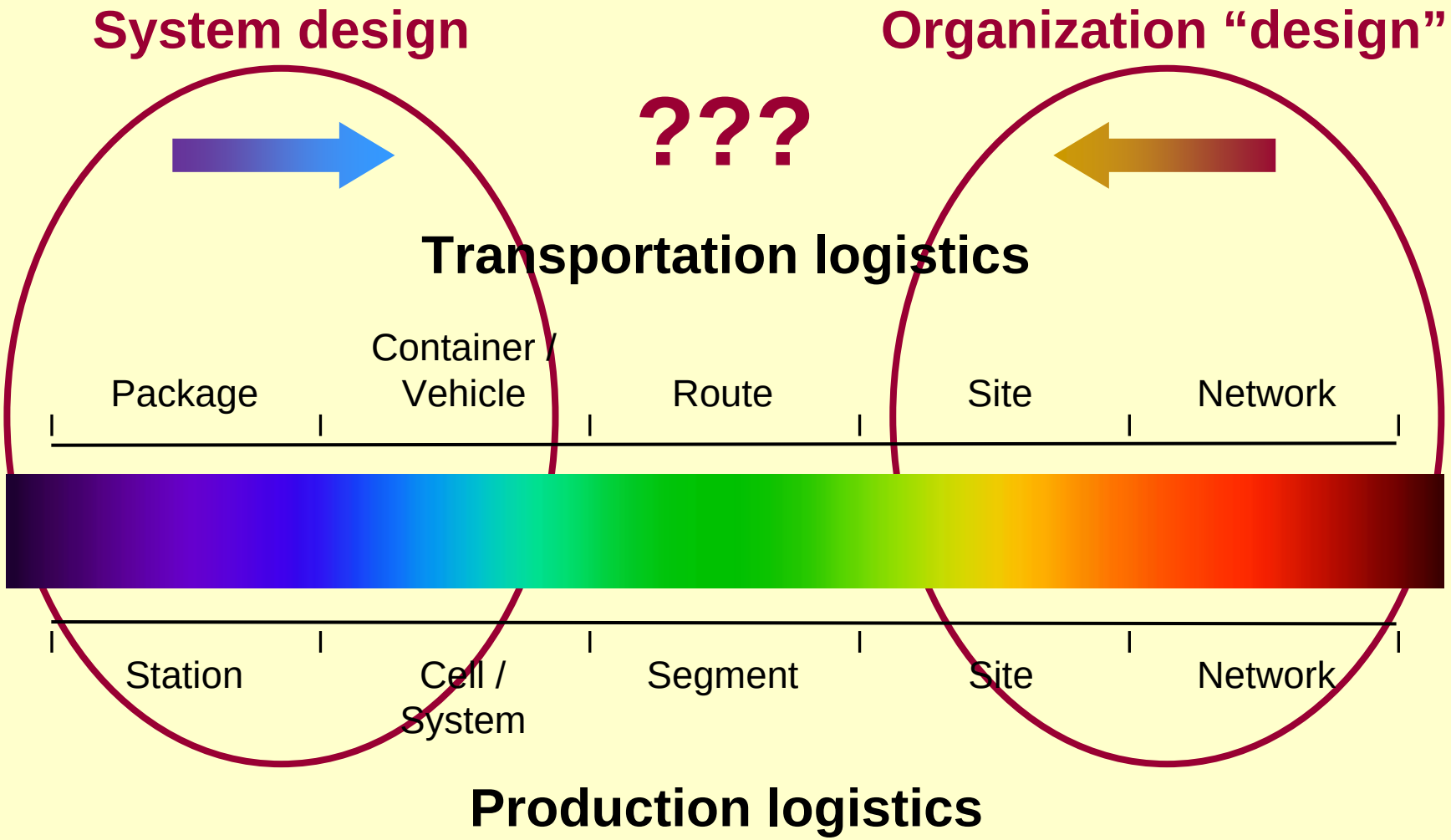
Influences on Logistic Control Design



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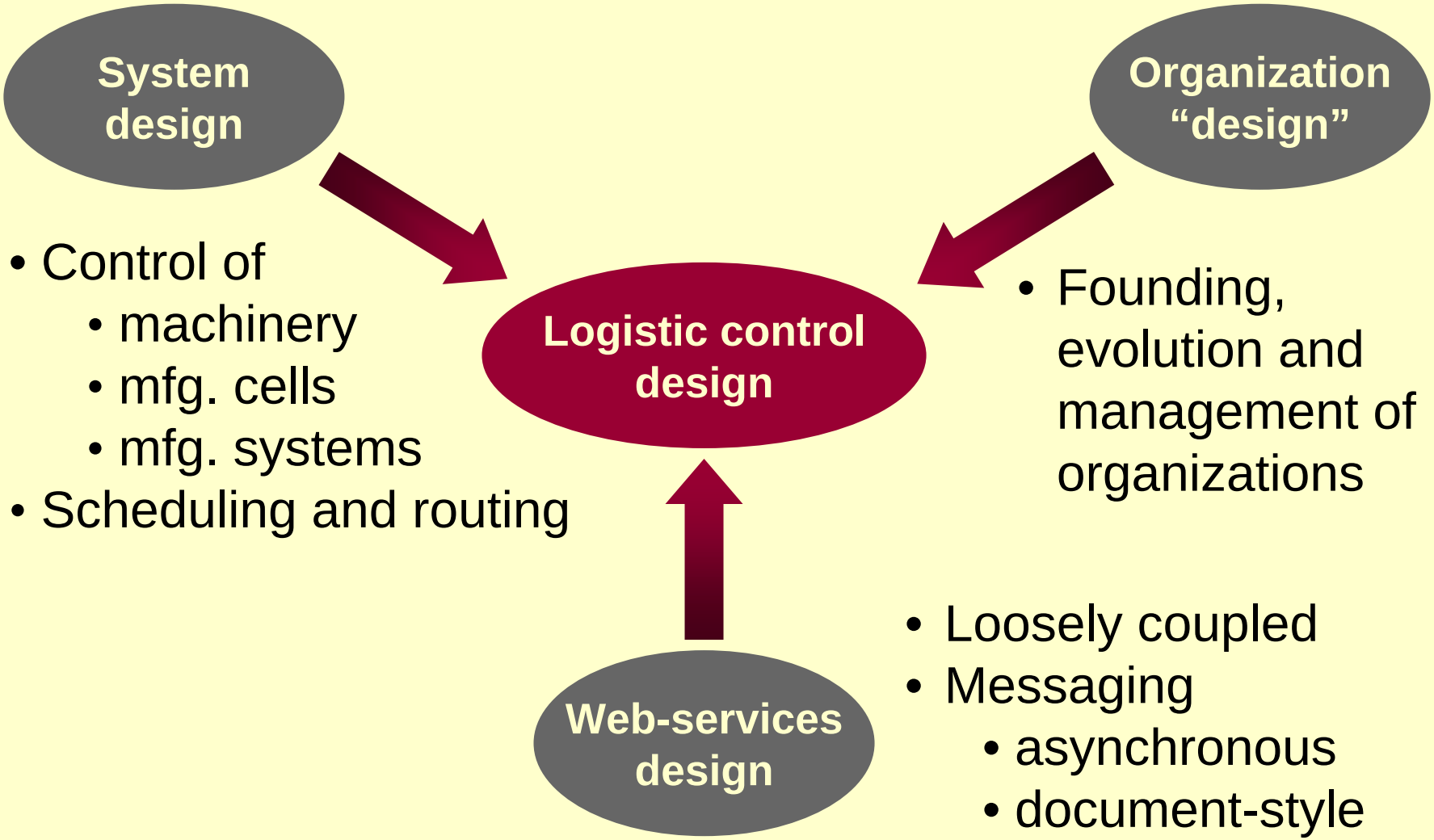
Influences on Logistic Control Design

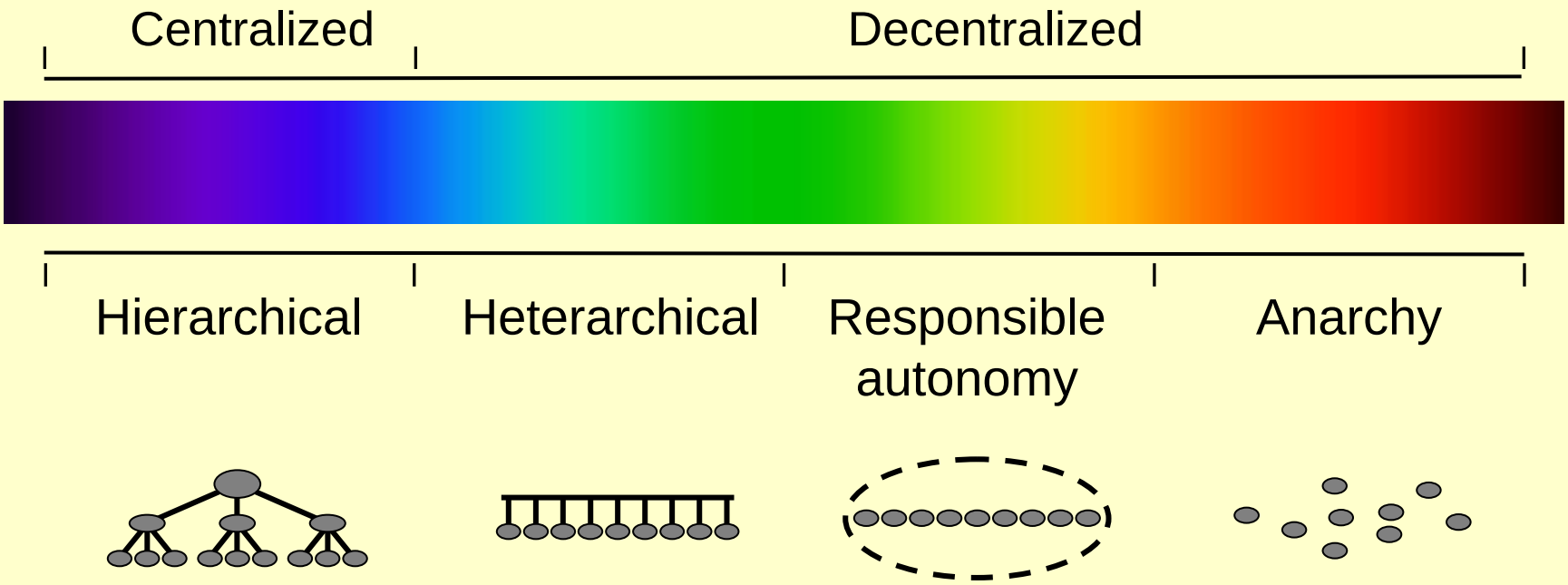


- Control of
  - machinery
  - mfg. cells
  - mfg. systems
- Scheduling and routing

- Founding, evolution and management of organizations

- Loosely coupled
- Messaging
  - asynchronous
  - document-style

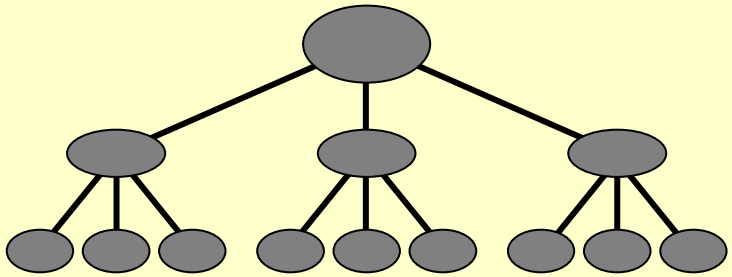
Spectrum of Organizational Structures



[adapted from Fairtlough, 2005]

Hierarchy

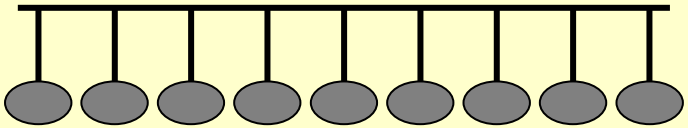
- A **hierarchy** is an organizational system in which each entity of the system (except for the top element) is subordinate to a single other element.



[adapted from Wikipedia, 2007]

Heterarchy

- A **heterarchy** is an organizational system in which entities share common goals and each entity shares the same "horizontal" position of power and authority, each having an equal vote. In a heterarchy, a node can be connected to any of its surrounding nodes without needing to go through or get permission from some other node. A heterarchy may be independent or at some level in a hierarchy (or a local heterarchy in another heterarchy).



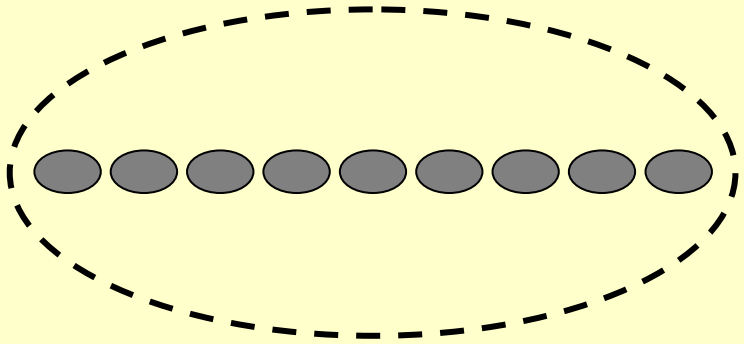
[adapted from Wikipedia, 2007]

Related terms:

- Decentralized
- Distributed
- Nonhierarchical

Responsible Autonomy

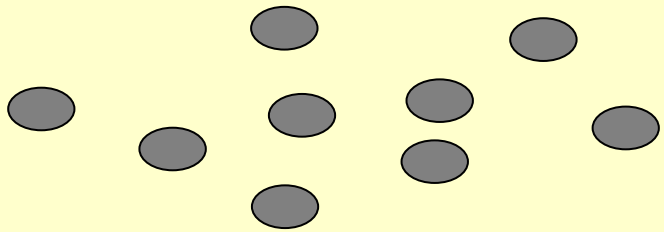
- A **responsible autonomy** is an organizational system in which each entity has autonomy to decide what to do, but is accountable for the outcome of the decision. Responsible autonomy requires clearly defined boundaries at which external direction stops. (The existence of accountability distinguishes responsible autonomy from anarchy.)



[adapted from Wikipedia, 2007]

Anarchy

- An **anarchy** is an organizational system in which there is no governing entity or group of entities and each entity has absolute liberty.



[adapted from Wikipedia, 2007]

Our Early Argument for Heterarchy

"…distributed computing concepts can be applied to produce modular, expandable and adaptable control systems with a high degree of hardware transparency…Cost benefits are likely to be accrued through improved flexibility, reliability, and performance of these systems…The attainment of these benefits depends on organizing the system into a set of autonomous processes supported on a group of processors connected by a communication network."

[from Duffie, 1982]

Hatvany's Argument for Heterarchies

"Highly centralized and hierarchically ordered systems tend to be rigid, constrained by their very formalism to follow predetermined courses of action. However carefully 'optimized' their conduct may be, it has been shown that this very property of inherent resistance to organizational change itself necessarily leads in due course to catastrophic collapses."

[from Hatvany, 1985]

Hatvany's Argument for Heterarchies [cont.]

"On the other hand, fragmentation of a system into small, completely autonomous units, each pursuing its own selfish goals according to its own, self-made laws, is the absurdity of primitive anarchy."

[from Hatvany, 1985]

Hatvany's Argument for Heterarchies [cont.]

"In the place of either of these, we suggest cooperative heterarchies…where the participant subsystems all have

- Equal right of access to resources
- Equal mutual access and accessibility to each other
- Independent modes of operation
- Strict conformity to the protocol rules of the overall system."

[from Hatvany, 1985]

“Cooperative Heterarchy”

- “…participants of such a heterarchy receive rights in return for assuming obligations. While there is no ‘higher level’ controller of the system, nevertheless each member must conform to certain rules, in order to obtain certain privileges…”
- “…one set of goals is concerned with the internal conduct of the sub-system and remains within the domain of its autonomy.”
- “…another set must always be dominant in each local set of evaluation criteria. This second set of goals is directed towards the optimal overall operation of the system, and it is these that introduce the property of cooperation.”

[from Hatvany, 1985]

2. Control of Manufacturing Equipment, Cells and Systems

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Principles for Partitioning

System functional requirements should be decomposed and partitioned into a set of quasi-independent, communicating entities using the following principles:

- There is a natural decomposition associated with the system.
- The result of decomposition is a set of quasi-independent entities with relatively weak interactions.
- All communication between entities takes the form of messages transmitted on a network.

[adapted from Duffie, 1990]

Principles for Partitioning [cont.]

- The physical system configuration should be transparent to the entities in the system, and entities should not need to know where other entities reside.
- Time-critical responses should be contained within entities and should not be dependent on time-critical responses from other entities.
- The resilience and viability of individual entities should be a major criteria.

[adapted from Duffie, 1990]

Principles for Fault Tolerance

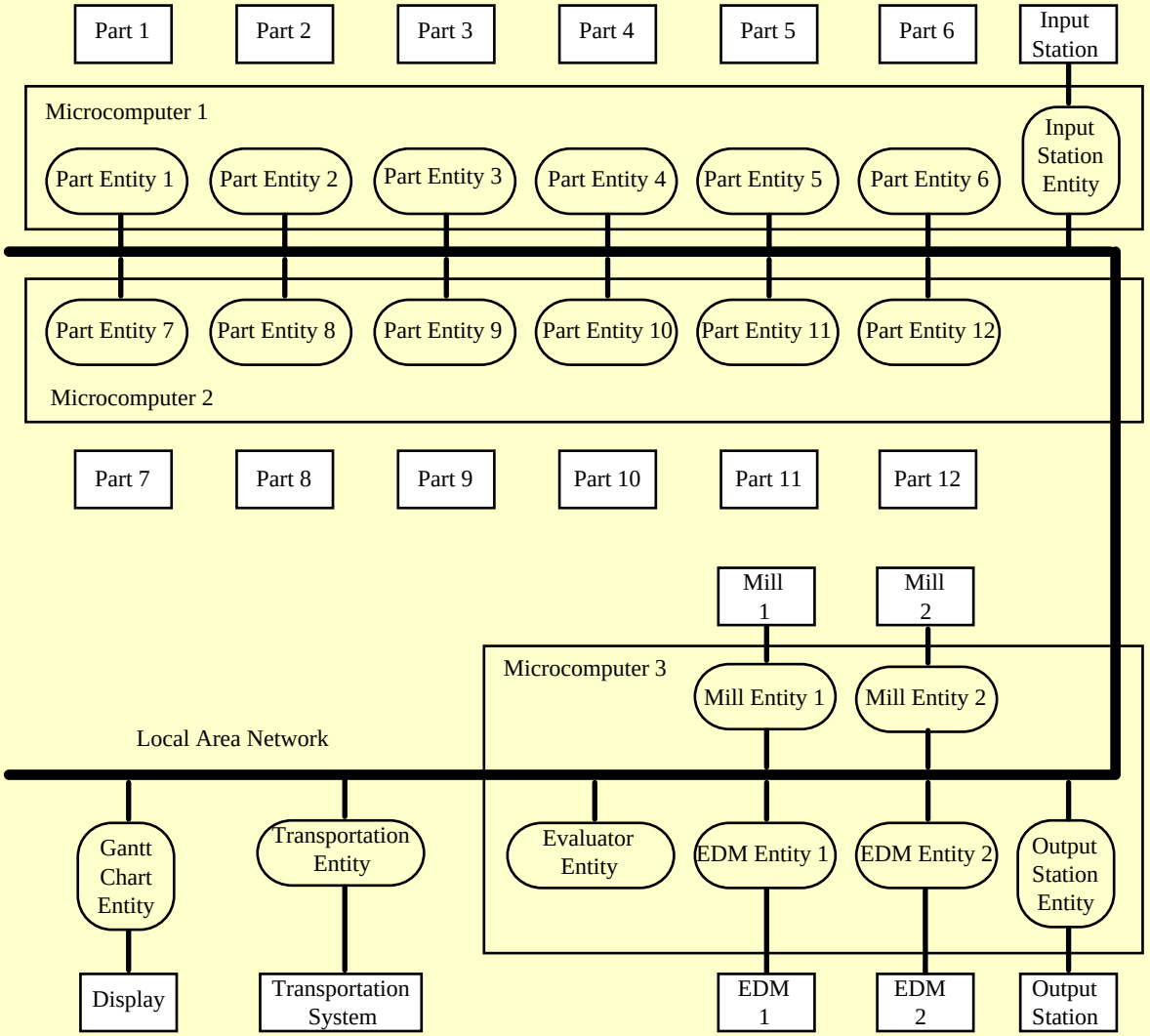
- Master/slave relationships should not exist between entities.

Trust?

- Entities should cooperate with other entities whenever possible.
- Entities should not assume that other entities will cooperate with them.
- Entities should delay establishing relationships with other entities for as long as possible, and should terminate these relationships as soon as possible.
- Information generated by an entity should be retained locally rather than globally, and communicated upon request to other entities.

[adapted from Duffie, 1990]

Example: Manufacturing Execution System



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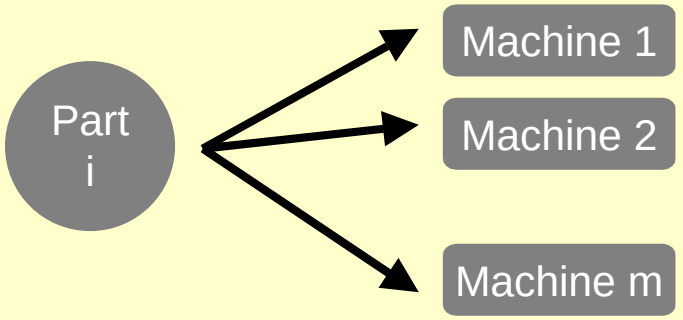
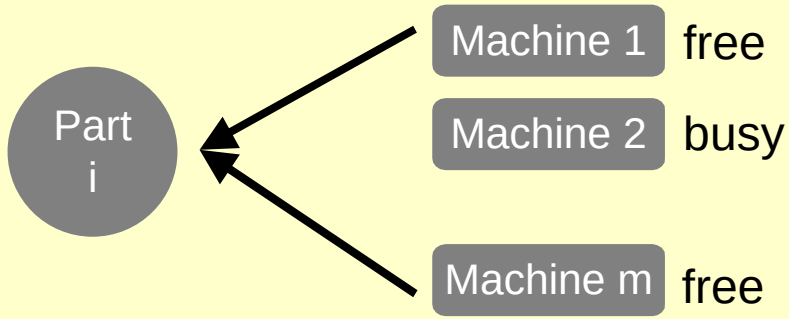
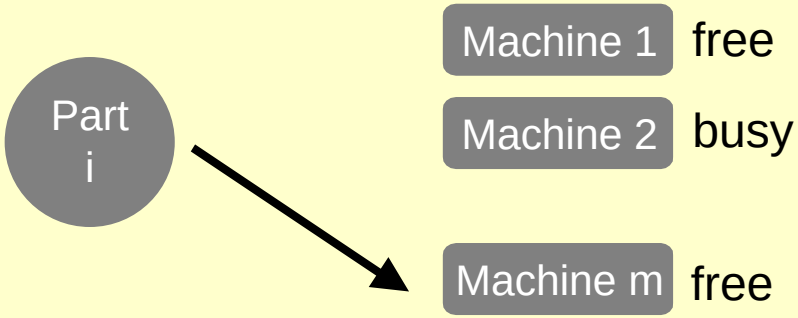
Example: Manufacturing Execution System



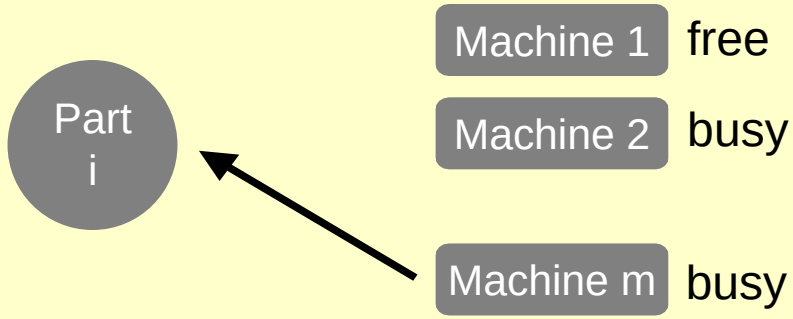
a) Part i broadcasts a request for a machine.



b) If a machine is free it sends a message to Part i.



c) Part i sends reservation to first machine that responds.

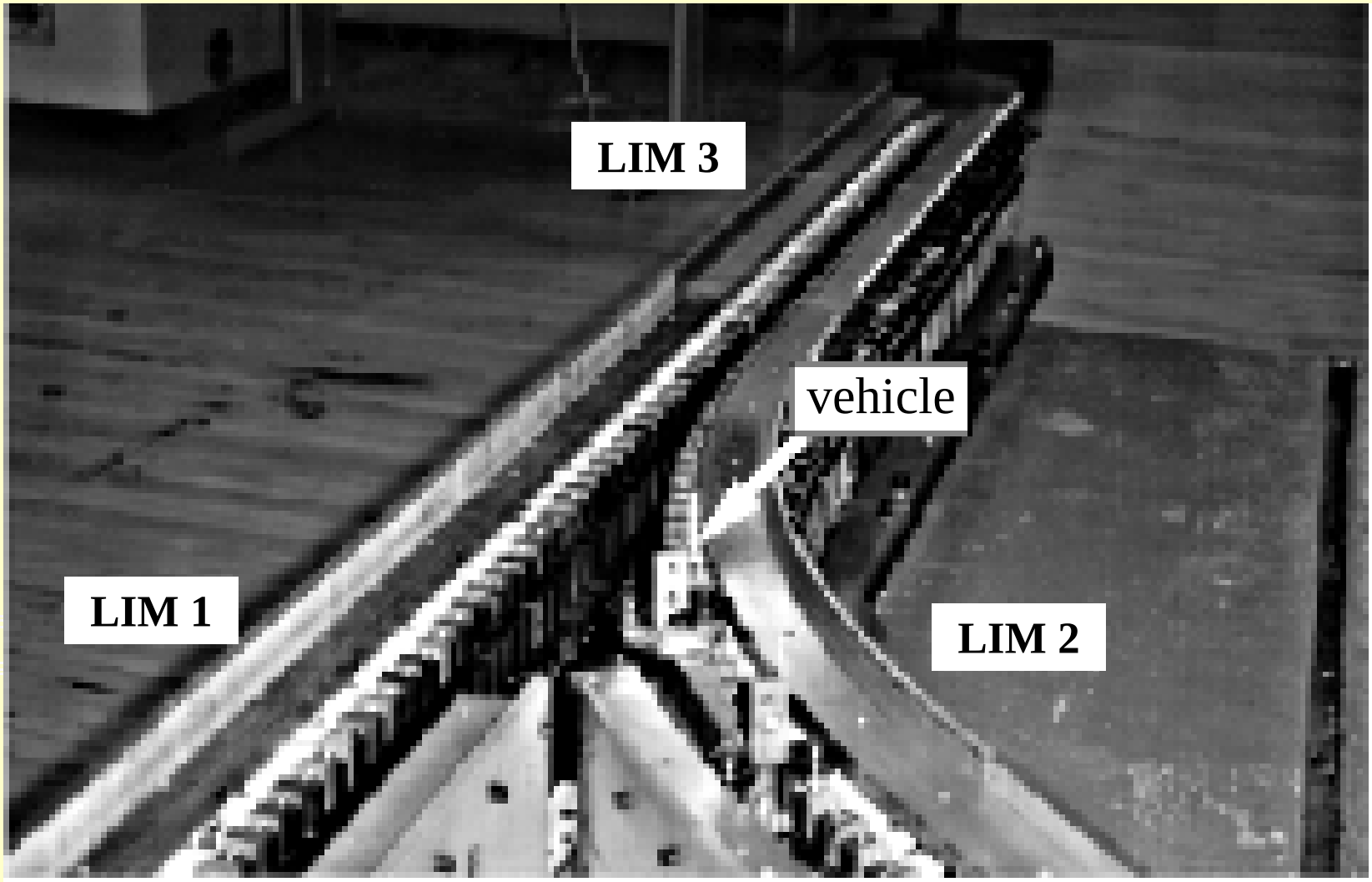


d) Machine confirms reservation of Part i if still not busy.

Example: Multitude of Propulsion Units

- High-speed material handling system for deliver of small parts and tooling
- Driven by approximately 1-meter long linear induction motor (LIM) segments
- Special segments for loading and unloading
- “Dumb” vehicle, “smart” track
- Need for distributed routing and dispatching
- Need for branching, merging and associated collision avoidance

Testbed: 3 LIMs in a “Y” Configuration



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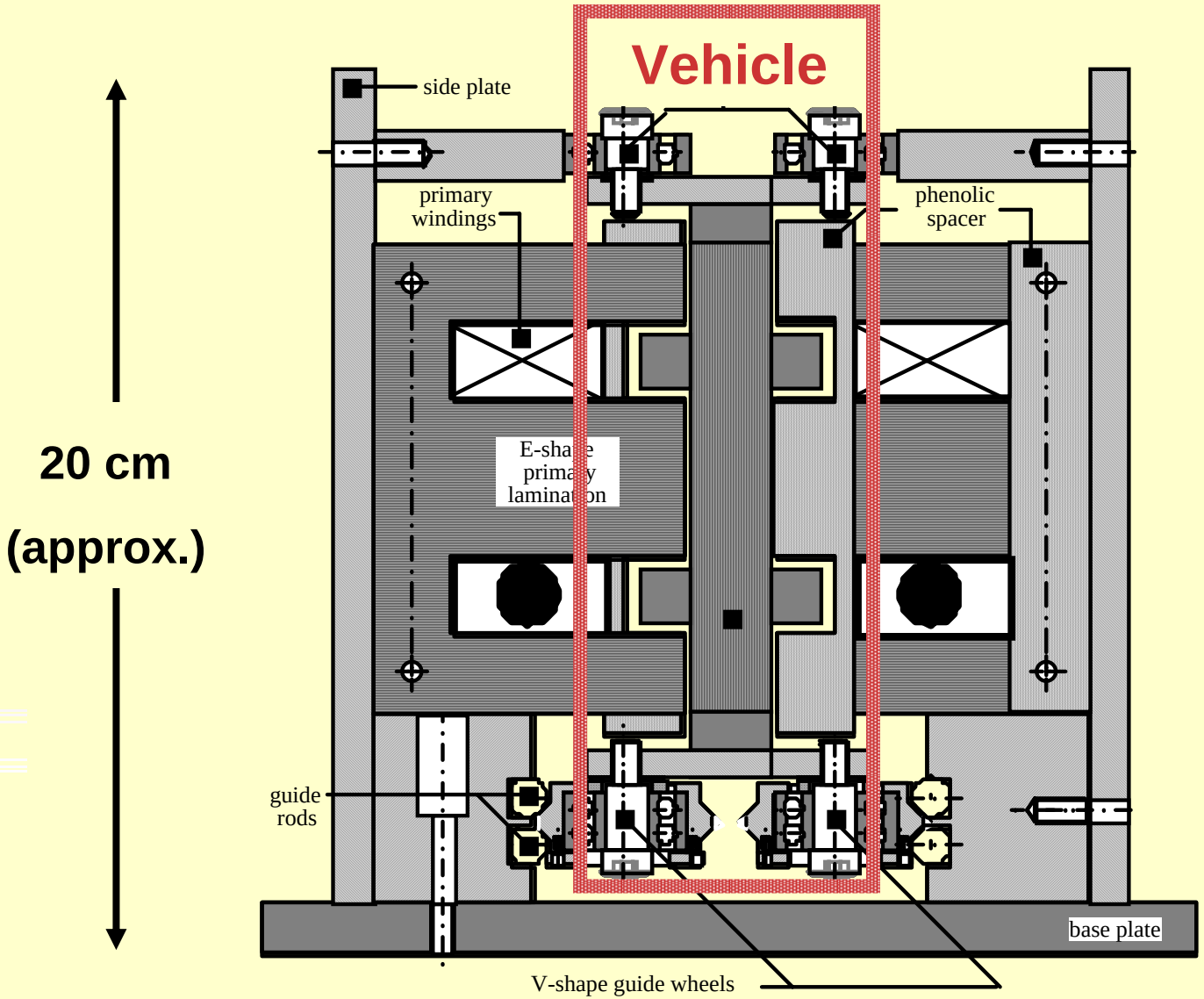
Vehicle and LIM Configuration



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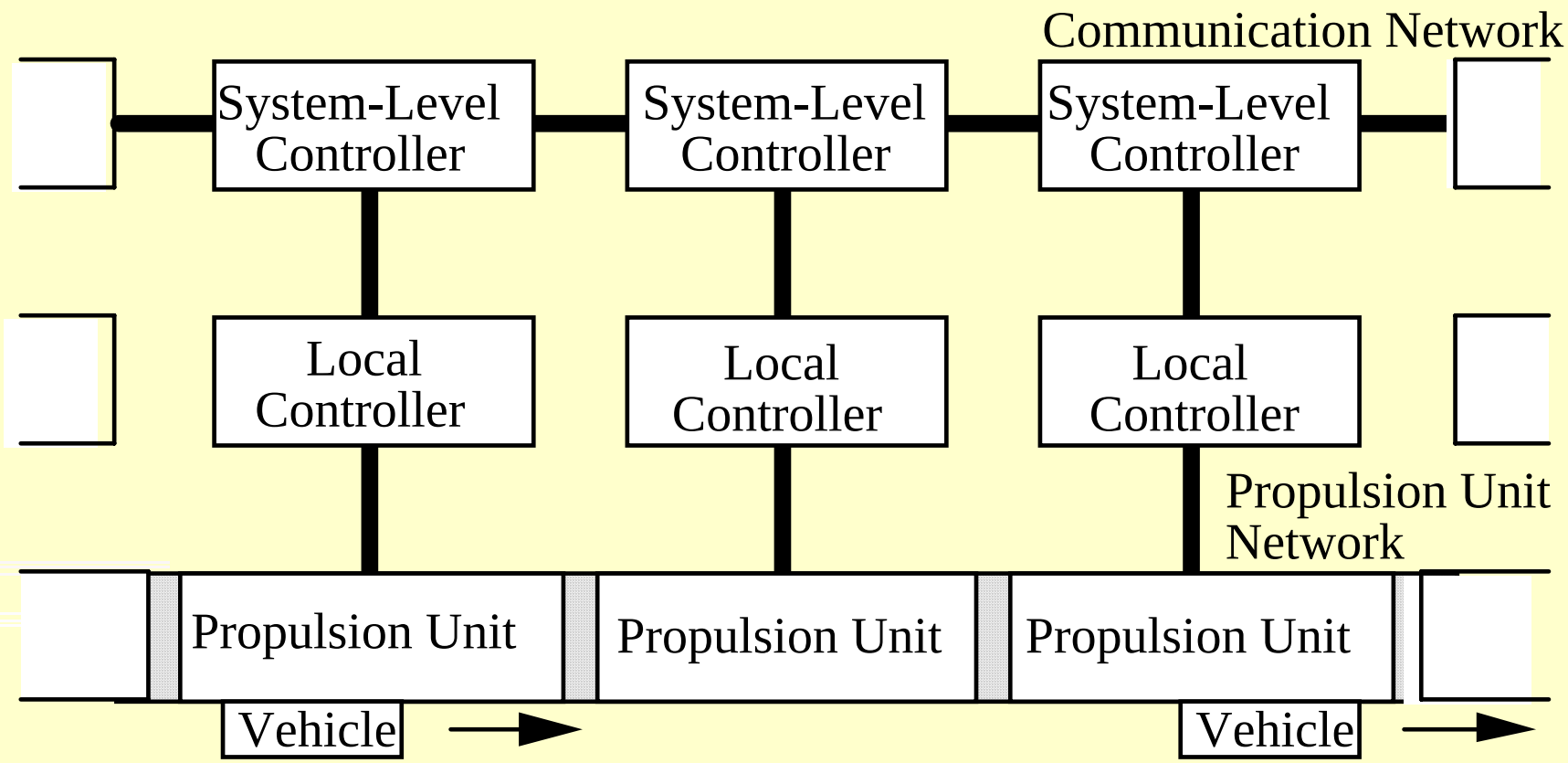
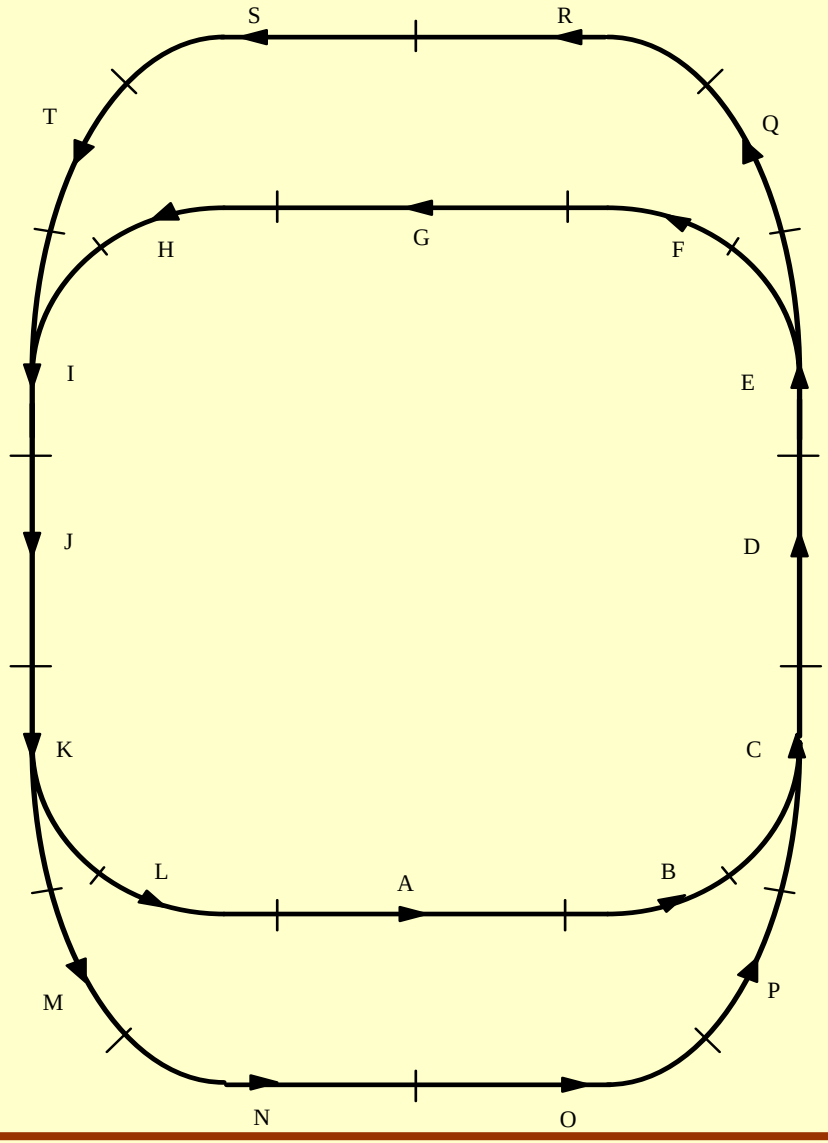
Communication Net = Propulsion Net



Example of a LIM Nework



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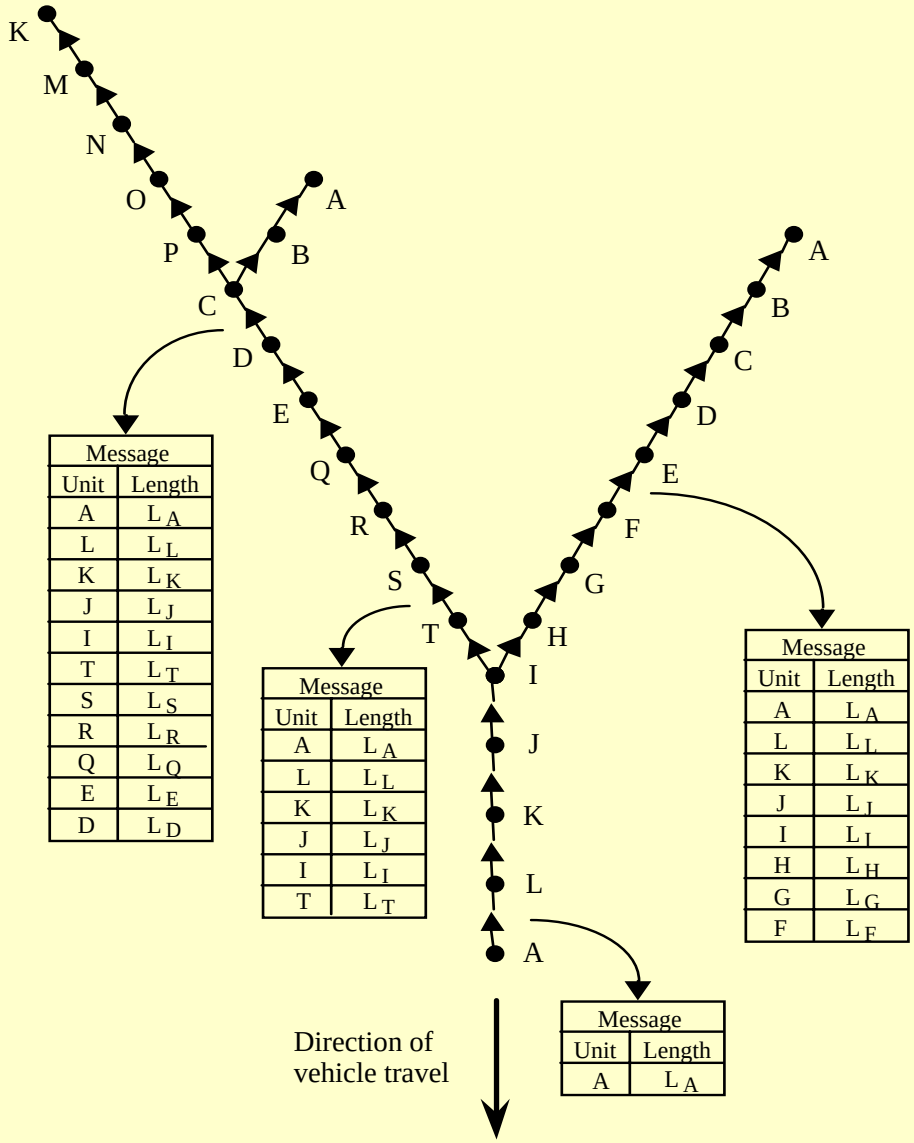
Dispatching Messages Propagate Upstream



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3. “Designing” Organizations

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Characteristics of “Wise Crowds”

“…under the right circumstances, groups are remarkably intelligent, and are often smarter than the smartest people in them.”

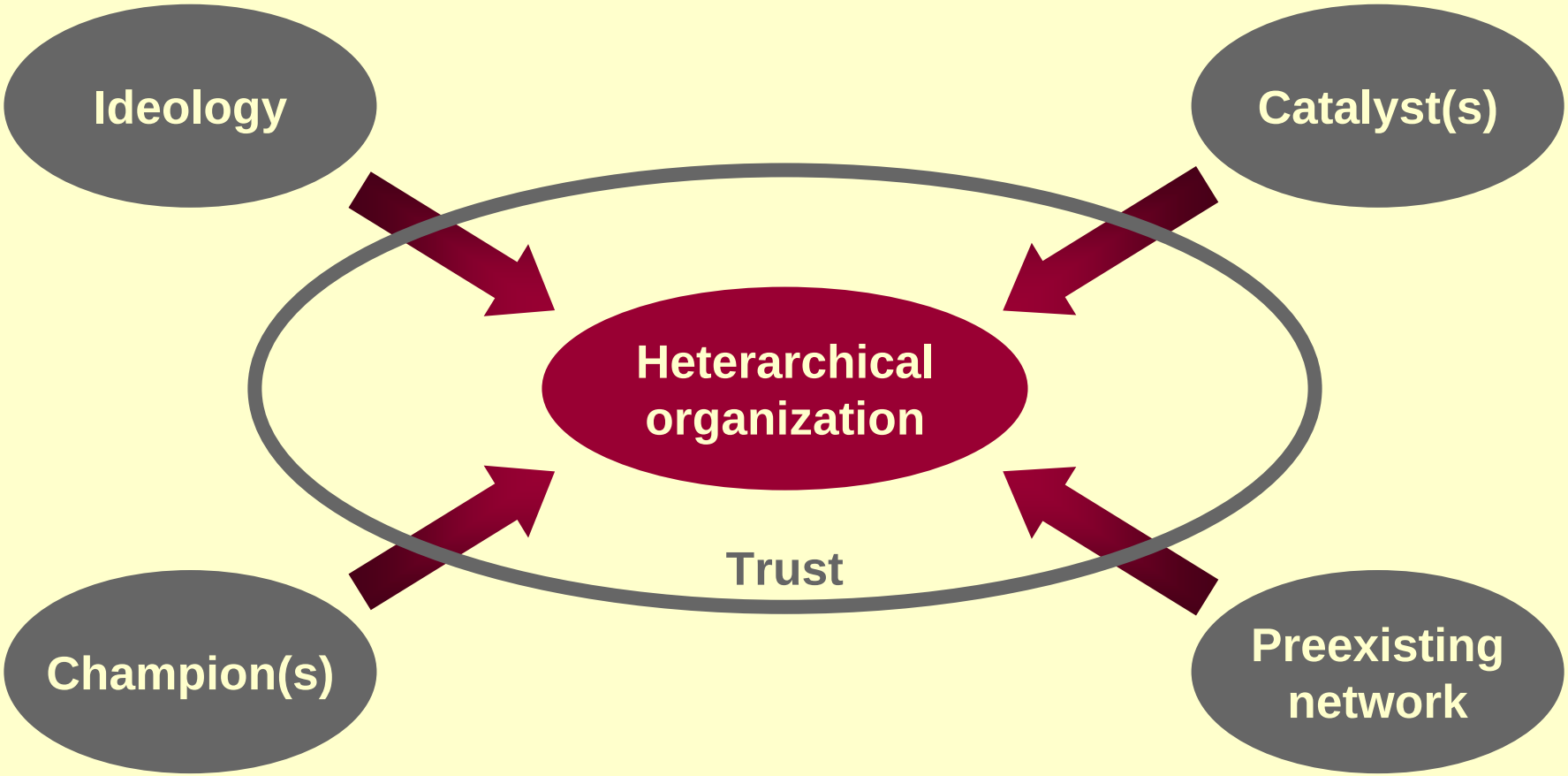
[from Surowiecki, 2004]

Requirements for “Wise Crowds”

- Decentralization
  - Entities are specialized and draw on local knowledge.
- Diversity of opinion
  - Each entity should have some private information, even if it is an “eccentric interpretation” of facts.
- Independence
  - Entities’ local judgments are not significantly influenced by the judgments of entities around them.
- Aggregation
  - Some mechanism exists for turning local judgments into collective decisions.

[adapted from Surowiecki, 2004]

“Designing” a Heterarchical Organization



[adapted from Brafman and Beckstrom, 2004]

Heterarchical Groups ("Circles")

- "…once you join, you're an equal. It's then up to you to contribute to the best of your ability…The Internet has allowed circles to become virtual: members join from their computers without ever leaving home."
- "Because circles don't have hierarchy and structure, it's hard to maintain rules within them; no one really has the power to enforce them. But circles aren't lawless. Instead of rules, they depend on norms…the backbone of the circle."

[adapted from Brafman and Beckstrom, 2004]

Heterarchical Groups ("Circles")

- "…Because they realize that if they don't enforce the norms no one will, members enforce the norms with one another. In doing so, members begin to own and embrace norms as their own. As a result of this self-enforcement, norms can be even more powerful than rules."

[adapted from Brafman and Beckstrom, 2004]

Catalysts

- "…a catalyst gets a decentralized organization going and then cedes control to the members."
- Catalysts' tools
  - Genuine interest in others
  - Loose connections
  - Mapping out how others fit into his social network
  - Desire to help
  - Meeting people "where they are"
    - Assumes a peer relationship
    - Listens intently
    - Inspires change without being coercive.

[adapted from Brafman and Beckstrom, 2004]

Catalysts' Tools [cont.]

- Emotional intelligence
  - Emotional connections come first
  - "Once there's an emotional connection, then and only then is it time to brainstorm and talk strategy."
- Inspiration
- Tolerance for ambiguity
  - "One day people are excited, the next they're ambivalent. One circle excels, another fails. There's no way to measure results. There's no way to keep track of all the members. There's no way to even know who is doing what, let alone where and when. To an outsider, the chaos might appear overwhelming."
  - "…ambiguity creates a platform for creativity and innovation."
- Receding

[adapted from Brafman and Beckstrom, 2004]

Ideology

- “Ideology is the glue that holds decentralized organizations together…”
- Long-lasting organizations tend to have powerful ideologies (League of Women Voters, Salvation Army, Alcoholics Anonymous, etc.)
- Internet-based organizations may have less powerful ideologies and may be shorter-lived (Wikipedia?, music sharing?, etc.)

[adapted from Brafman and Beckstrom, 2004]

Preexisting Network

- Most highly successful decentralized organizations have been launched from an existing platform, even in pre-Internet days.
- The Internet now serves as the platform of choice from which a wide variety of decentralized organizations can be launched.

[adapted from Brafman and Beckstrom, 2004]

Champions

- Champions “operate well in nonhierarchical environments.”
- Champions “tend to be more like salesmen than organizers or connectors.”
- Heterarchical groups with complementary catalysts and champions have a high probability of success.
  - A catalyst builds the organization, person by person.
  - A champion inspires the group, but is not “the boss.”

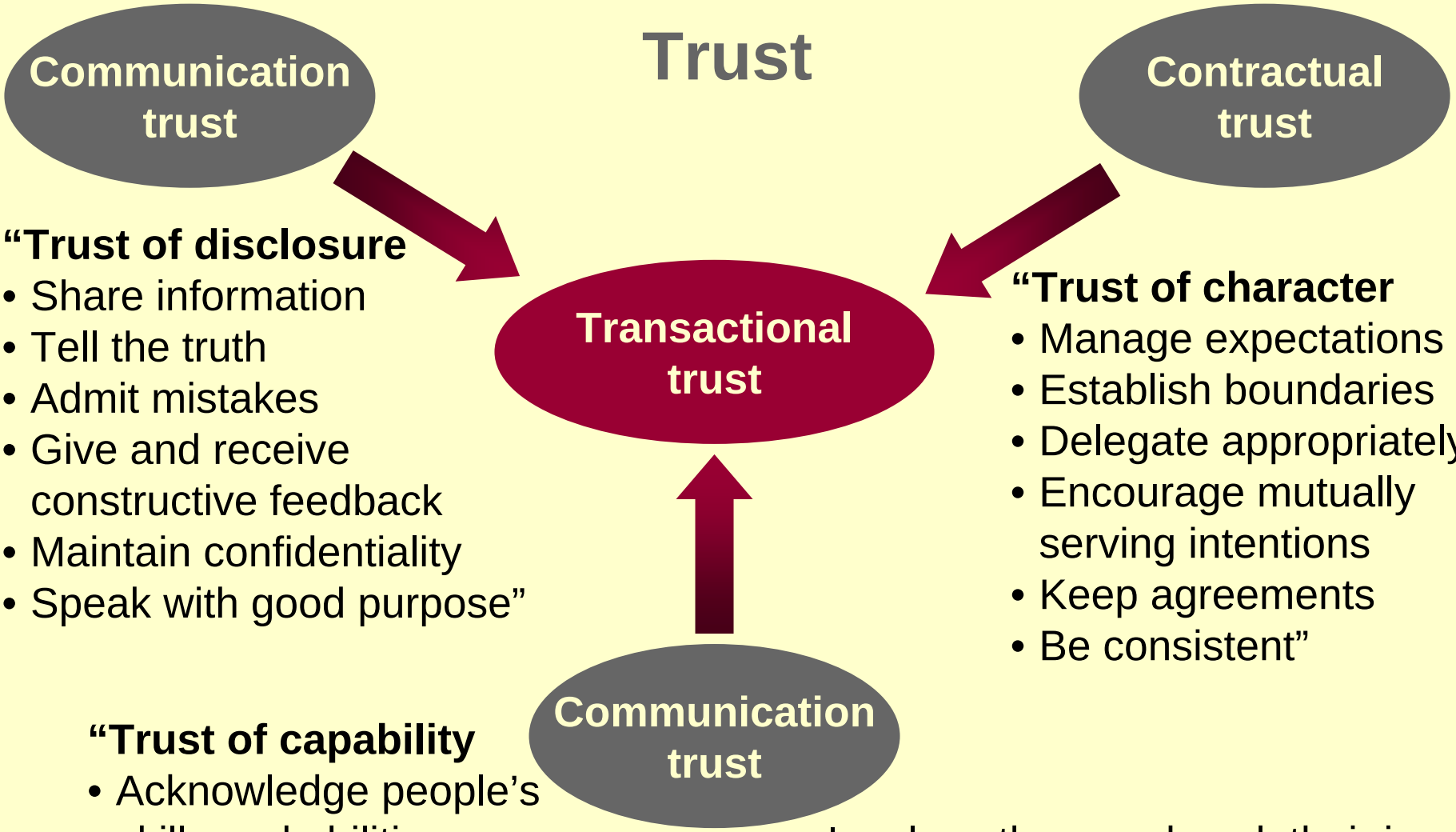
[adapted from Brafman and Beckstrom, 2004]

Trust

"With a flattened hierarchy, you never know what people are going to do. You can't control the outcomes...All you can control is whether people have personal relationships with each other based on trust."

[adapted from Brafman and Beckstrom, 2004]

Trust



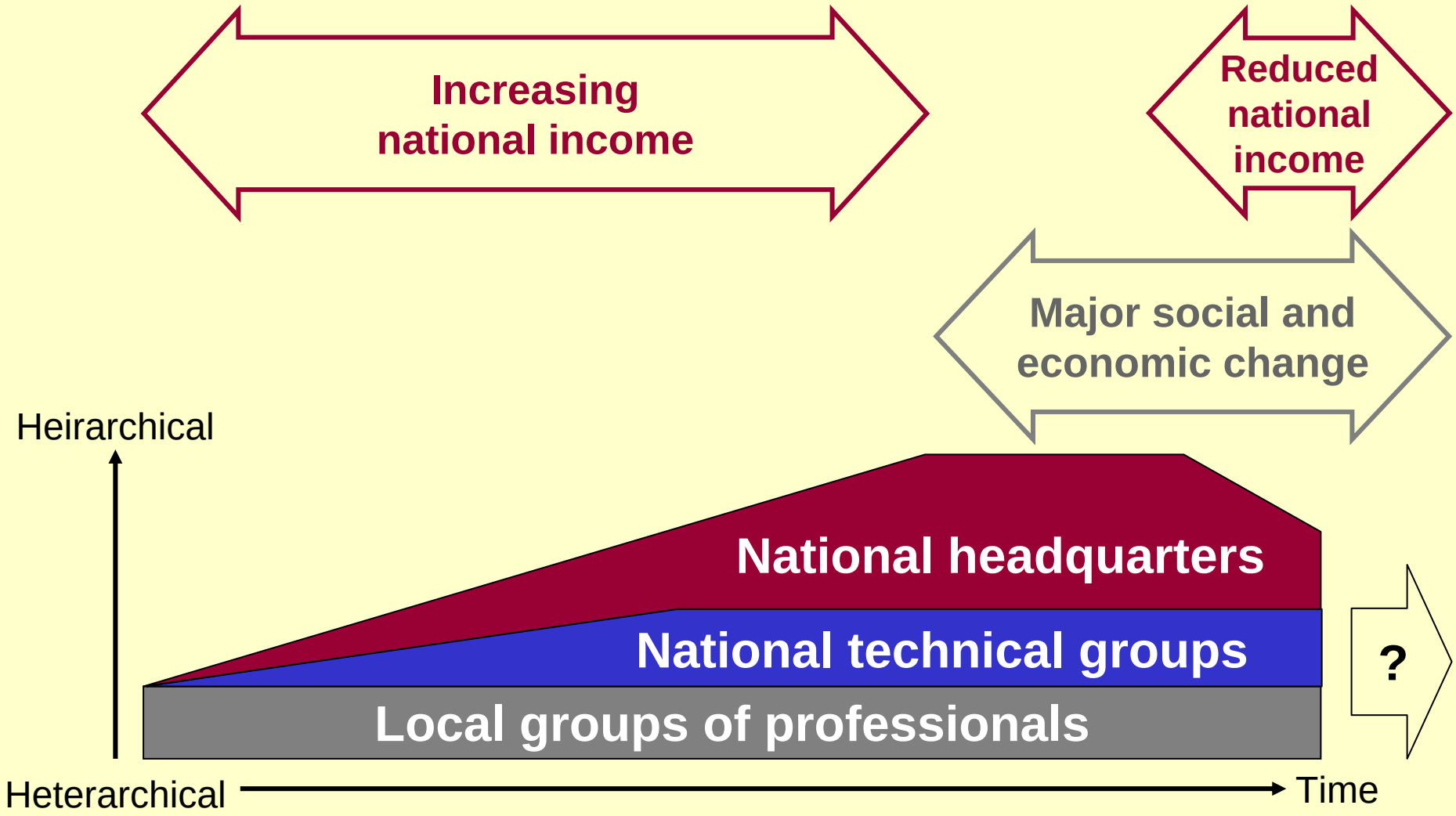
"Trust of disclosure
- Share information
- Tell the truth
- Admit mistakes
- Give and receive constructive feedback
- Maintain confidentiality
- Speak with good purpose"

"Trust of character
- Manage expectations
- Establish boundaries
- Delegate appropriately
- Encourage mutually serving intentions
- Keep agreements
- Be consistent"

"Trust of capability
- Acknowledge people's skills and abilities
- Allow people to make decisions
- Involve others and seek their input
- Help people learn skills"

[from Reina & Reina, 2006]

Example: Professional Organization Evolution



4. Web Service Architectures

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Options for Specifying Logistic Systems

Specifications for control of logistic systems

- Processes required; Examples:
  - Check inventory
  - Ship order, etc.
- Rules for executing the processes; Examples:
  - Cancel order if insufficient inventory
  - Reroute shipment if primary route is unavailable

1. Embed specifications in a centralized logistic control entity in a hierarchical structure?
   - Specifications are in a single place
   - Does not distribute intelligence
   - Tight coupling

[adapted from Kaye, 2003]

Options for Specifying Logistic Systems

2. Embed specification subsets in specialized entity in a heterarchical structure?
   - A single change in a logistic system could require a cascade of changes in multiple entities.
   - Tight coupling
3. Embed specifications in documents communicated between specialized entities in a heterarchical structure?
   - Requires local interpretation of document schema
   - Ideal for Web Services

[adapted from Kaye, 2003]

Web Services

- Web services are accessed over a network, such as the Internet, and are executed on the remote systems that host the requested services.
- Web services are delivered by heterogeneous, distributed providers who are linked using service-oriented architectures (SOAs).
- Web services are loosely coupled, achieving interoperability in ways that are changeable and accommodate unanticipated future applications.

[adapted from Kaye, 2003]

Service-Oriented Architectures (SOAs)

- The goal of SOAs is to allow services (large collections of functionality) to be connected together to form ad-hoc processes.
- No interactions between the services are specified within the services themselves. SOA services therefore are loosely coupled.
- Interaction between services, to create the process, is specified externally with the “intent du jour” driven by newly emergent requirements.

[adapted from Wikipedia, 2007]

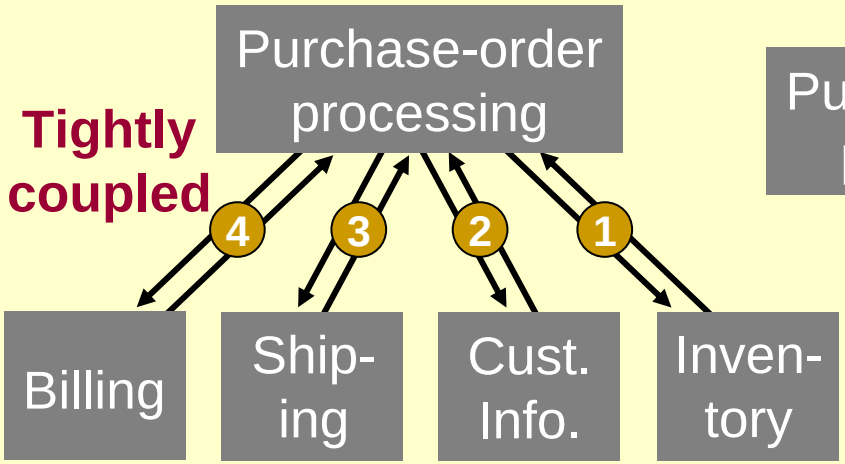
Coupling in Web Services

	Tightly coupled	Loosely coupled
Interaction	Synchronous	Asynchronous
Messaging style	RPC	Document
Message paths	Hard coded	Routed
Technology mix	Homogeneous	Heterogeneous
Data types	Dependent	Independent
Syntactic definition	By convention	Published schema
Bindings	Fixed and early	Delayed
Software objective	Re-use, efficiency	Broad applicability
Consequences	Anticipated	Unexpected

[adapted from Kaye, 2003]

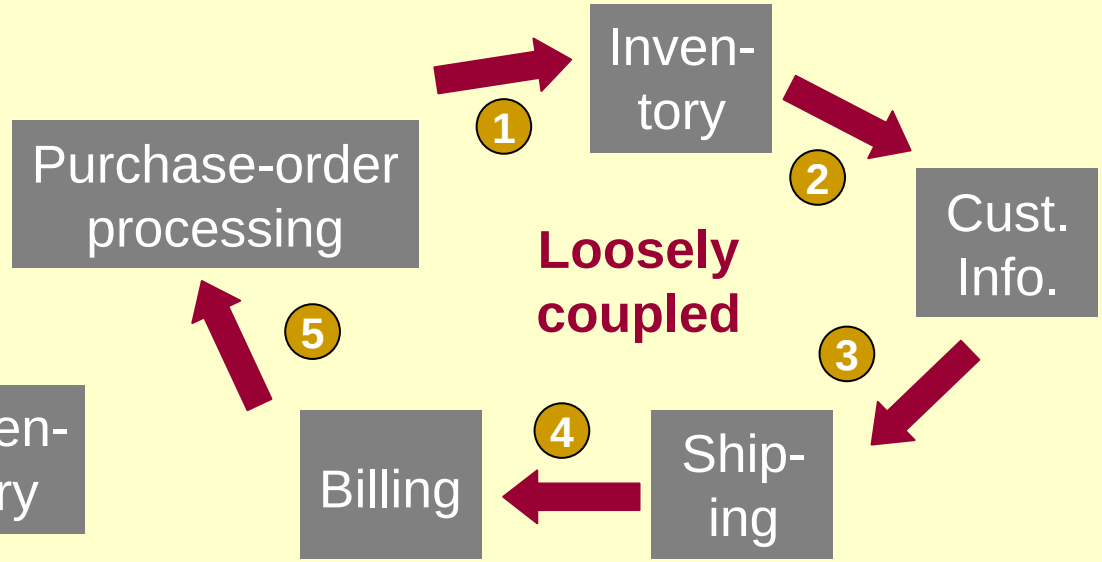
Example: Purchase-Order Processing

Traditional architecture



- Hierarchical structure
- Synchronous, bidirectional interaction
- RPC (Remote Procedure Call) messaging style
- Hard-coded function sequence

Web services architecture



- Heterarchical structure
- Asynchronous, unidirectional interaction
- Document messaging style
- Routed function sequence

[adapted from Kaye, 2003]

Document Contents for Logistic Systems

- Schema for the document
- Processes required
- Rules for the processes
- Initial data
- Appended data

Route through service entities

Data used in decision-making, scheduling, routing, etc., including data (results) appended by entities upstream in the route.

Schema for the Document

- Description of the document, particularly its structure, content
- How data in the document is to be interpreted:
  - number
  - Date
  - Boolean, etc.
- The document must be well-formed with respect to the schema, which must be well-documented and consistent.
- Optionally, the schema can be defined externally (a “standard”)

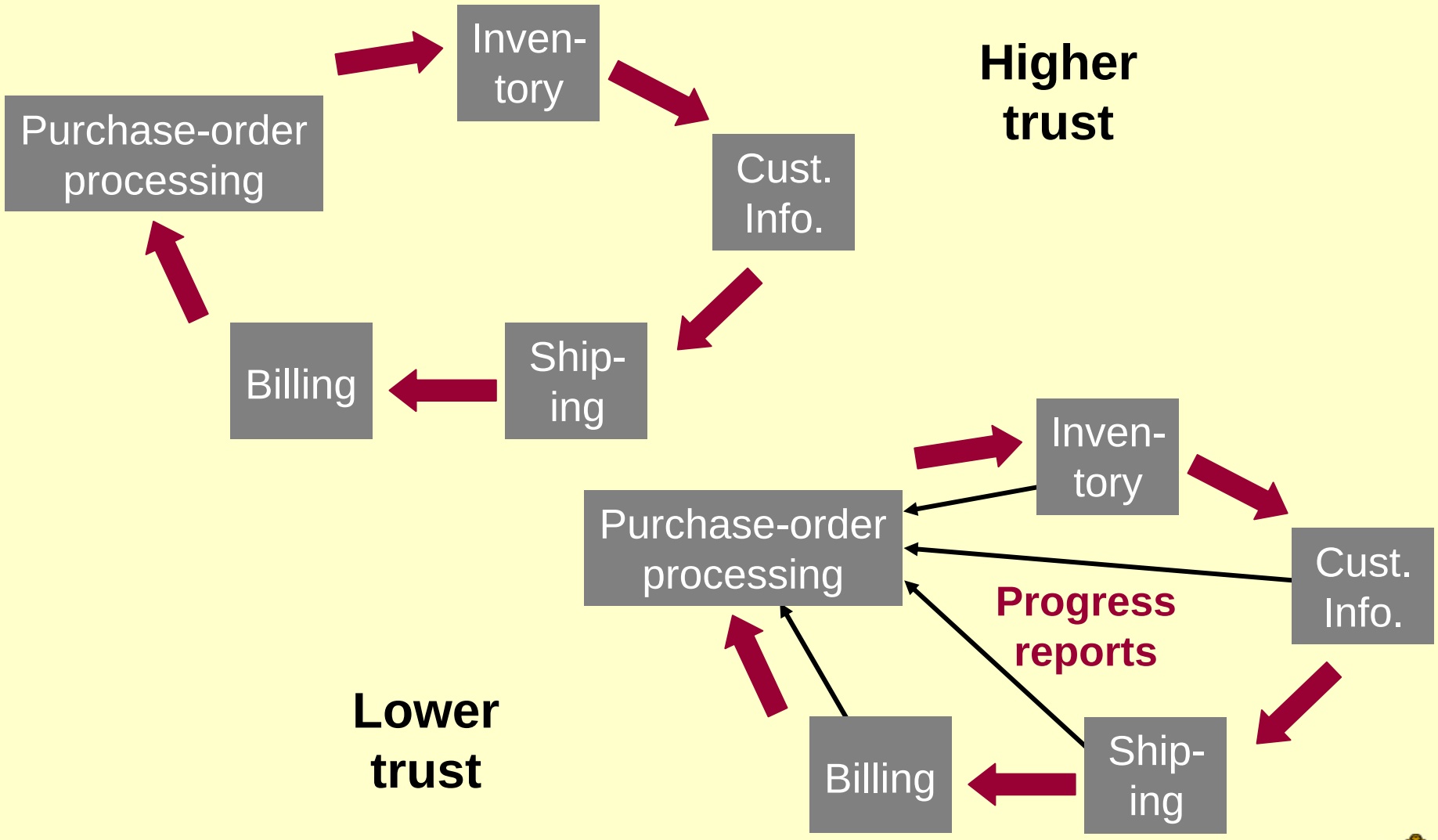
Specialized Logistic Process Entities

- Functional components of logistic processes should be distributed between entities according to principles of modularity.
- Entities should only need to handle that portion of the information in a document that is relevant to the function(s) the entity performs.
- Entities should not need to know details of the function(s) performed by previous or subsequent entities on the document's route.
- Entities should not need to know the overall purpose of a document; an entity should be able to process any document that requires that entity's function(s).

Trust

- Distribution, loose coupling, document routing and asynchronous messaging can create a “fear of betrayal” in operation of such a system.
- Trust is required that the document will be returned after a (possibly long) delay.
- Trust that services have been provided as called for in the document and as confirmed by data appended to the document by the service providers. (If failure to provide services has been documented, the process can react in the proper manner.)

Levels of Trust



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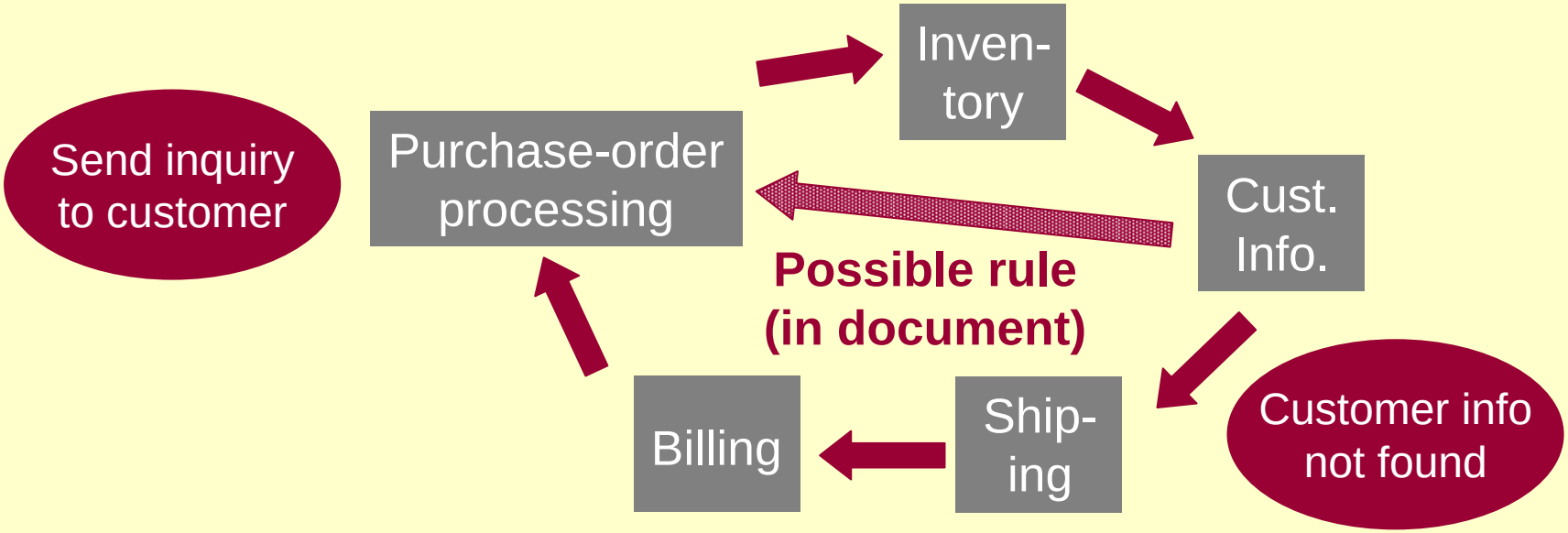
Trustworthy Service Provider



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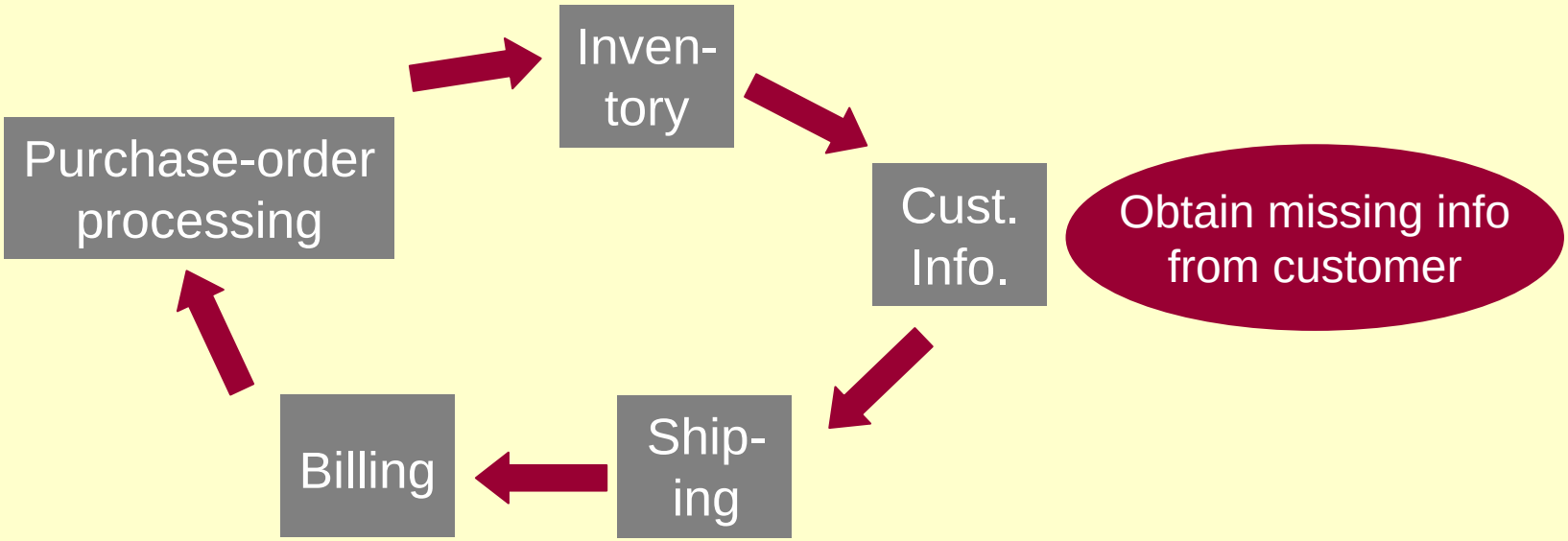
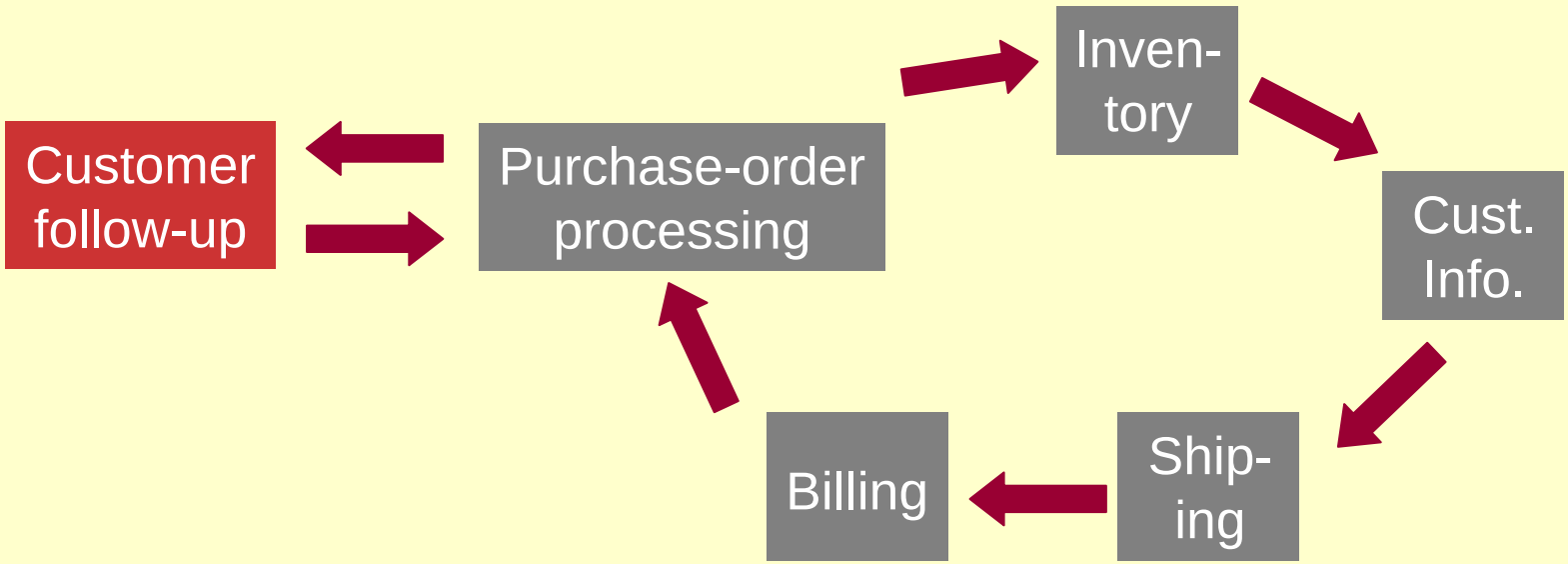
Evolution: New Service Provider

A new provider might be found in the future that provides more or better service.



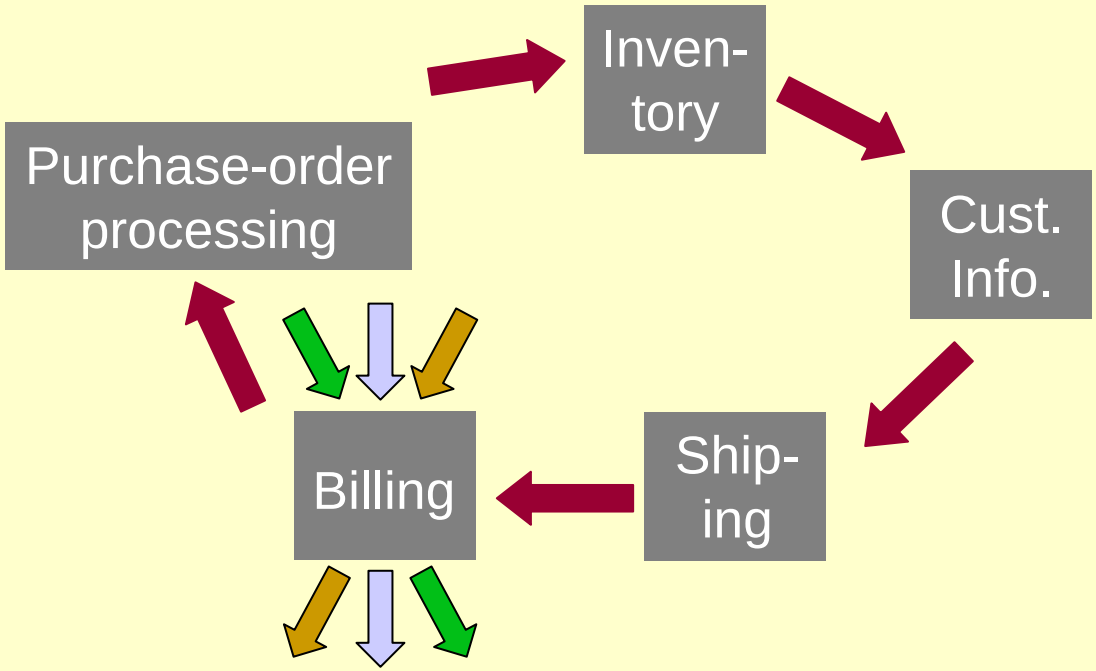
Evolution: New Service

A new customer follow-up service might be needed in the future to assess customer satisfaction.



Unexpected Opportunity (Broad Applicability)

Developing the “Billing” service so that it is broadly applicable may lead to its use by other processes or to marketing of the web service.



5. Evolution of Heterarchical Controls for Logistic Systems

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Detecting Hierarchy and Heterarchy

- Is there an entity in charge?
- Are there headquarters?
- Is there a clear division of roles?
- If an entity is removed, is the organization harmed?
- Are knowledge and power concentrated? Distributed?
- Is the organization rigid? Flexible?
- Can you count the number of entities?
- Are entities motivated by the organization? Self-motivated?
- Do entities communicate through intermediaries? Communicate directly?

[adapted from Brafman & Beckstrom, 2004]

Characteristics of Heterarchical Orgs.

- Knowledge, decision making and responsibility are spread throughout the organization.
- Functionally (viewed from the outside), it can be difficult to distinguish a heterarchy from a hierarchy.
- The organization can evolve and grow quickly and easily.
- A decentralized organization tends to become more decentralized when attacked.
- Profit making becomes more difficult as an organization becomes more decentralized.

[adapted from Brafman and Beckstrom, 2004]

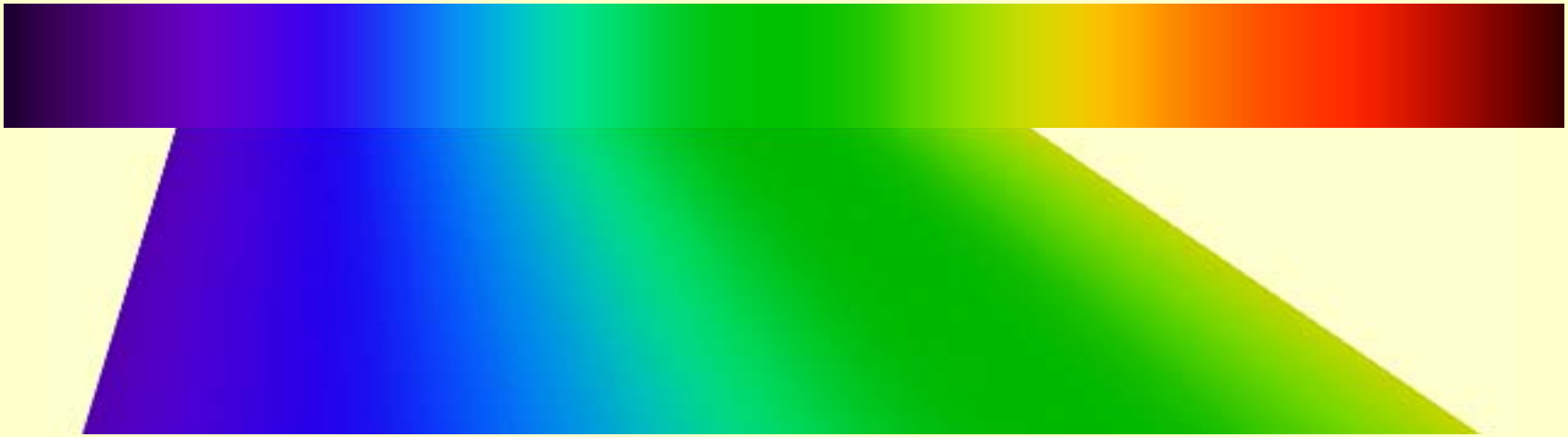
Monitoring Heterarchical Organizations

- Monitoring individual entities
  - How active are they?
  - How distributed is the network?
  - Are the entities independent?
  - What kind of connections do they have between them?
- Monitoring heterarchical organizations
  - Do entities continue participating?
  - Is the network growing?
  - Is it spreading?
  - Is it evolving?
  - Is it becoming more or less decentralized?

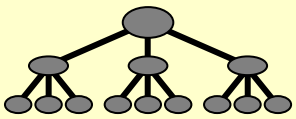
[adapted from Brafman & Beckstrom, 2004]

Changing the Control Structure

Hierarchical | Heterarchical | Responsible autonomy | Anarchy



What is the right structure for control today? Tomorrow?



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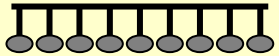

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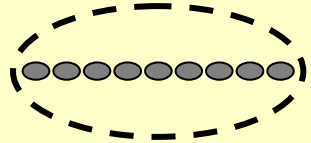

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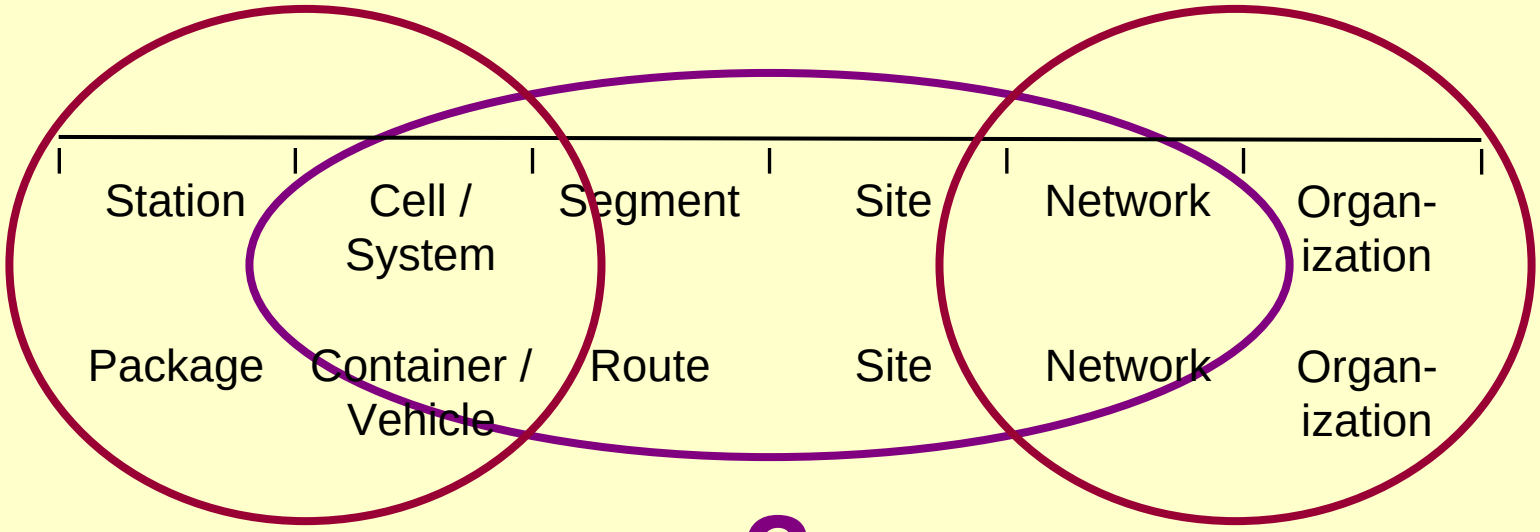
Design versus Evolution

Heterarchical control of machinery and mfg./trans. execution

Heterarchical control of dynamic logistic systems

Heterarchical growth and evolution of organizations and networks



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One Vision for the Future

- Many production and logistic networks and their associated logistic processes will emerge, evolve and disappear rapidly due to seen and unforeseen forces such as globalization, Internet and local innovation.
- Networks and logistic systems with **autonomous** logistic processes organized in **heterarchical structures** using **web services** will be more capable of rapid **evolution** and surviving unexpected competition.
- Their complexity will evolve **dynamically** rather than be designed, with **incremental** investments.
- Profits may be minimal in delivering logistic processes to such networks. “The small shall be big.” [Friedman]

Evolution is Toward Heterarchical Systems

- Will the designers of controls for today's logistic processes dare to design them?
- Will tomorrow's users dare to use them?

"Time will tell," but the opportunity exists!

Thank you for listening!

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Acknowledgement

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