Principles from the Past

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Internet 0
MIT
October 1, 2004
My Early Years at MIT

Information Flow in Large Communication Nets

July 24, 1961

Leonard Kleinrock
“The purpose of this thesis is to investigate the problems associated with information flow in large communication nets....”

“The nets under consideration consist of nodes, connected to each other by links. The nodes receive, sort, store, and transmit messages that enter and leave via the links....”

Under what conditions does the net jam up?

Time lapse between initiation and reception

Channel capacity

Storage capacity size

Transient behavior and recovery time

Routing doctrine
A Mathematical Theory of Data Networks

- Channel capacity limited
- Mean response time as key metric
- Analytic model set up and solved
- Optimal assignment of channel capacity
- Choice of priority queueing discipline and the introduction of packet switching
- Distributed routing procedure
- Design of topological structure
- Elucidated underlying principles of data networks

Systems of Flow

1. Steady flow through a single channel
   • **Trivial** and deterministic

2. Unsteady flow through a single channel
   • Queueing theory; **stochastics** get you

3. Steady flow through a network of channels
   • Network flow theory; **multicommodity** gets you

4. Unsteady flow through a network of channels
   • A New domain; **everything gets you**!
     • Jackson’s networks of queues (1957)
     • Kleinrock’s Independence Assumption cracks the problem wide open
Key Equation for Networks

\[ T = \sum_{i} \frac{\lambda_i}{\gamma} \]

This is EXACT!!

- \( T \) = Average network delay
- \( \lambda_i \) = Traffic on channel i (Msg/sec)
- \( \gamma \) = Network throughput (Msg/sec)
- \( T_i \) = Average delay for channel i

But how do you find this term?
The Independence Assumption

Each time that a message is received at a node within the net, a new length is chosen for this message independently from an exponential distribution.

- Without the Independence Assumption, the problem is intractable.
- With the Independence Assumption, the problem is totally manageable!!

We get:

\[ T_i = \frac{1}{\mu C_i - \lambda_i} \]

where \( \mu C_i \) = Capacity of channel \( i \) (Msg/sec)
Flow Control

Seeking principles and underlying behavior
The Holland Tunnel

Manhattan

New Jersey

Hudson River

Holland Tunnel
FLOW CONTROL

Whoa!!

PING!

COMPUTER NET

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Constraints are Dangerous
Flow Control in Networks
Throughput

Loss

\( \lambda \rightarrow \text{Network Cloud} \rightarrow \gamma \)

\( \lambda - \gamma \rightarrow \text{LOSS} \)

\( \gamma \rightarrow \text{Throughput} \)

\( \gamma_0 \)

\( \text{CAPACITY} \)
Distributed Control

- **Routing Procedures:**
  - Easy to design
  - Hard to analyze (dynamic)

- **Flow Control:**
  - Hard to design
  - Outrageously difficult to analyze
  - Absolutely essential

- **Guaranteed to GET you!**
Response Time vs Throughput

\[
\text{POWER} = \frac{\text{Throughput}}{\text{Response Time}} = P = \frac{\gamma}{T(\gamma)}
\]

Do you want to operate here?
Or here?

\[T(\gamma)\]

Response Time

\[\gamma(\lambda)\]

Max Power Point

Response Time vs Throughput

At Max Power
\[ N^* = 1 \]

\[ T(\gamma) \]

Response Time

\[ \gamma(\lambda) \]

Throughput

Max Power Point

\[ \gamma^* \]
Use Your Intuition

Only 1 customer

Insight: Just keep the pipe full!

\[ T = \text{Min} \]
\[ \text{Eff} = \text{Max} \]
Highly Structured Systems

- A.M. Radio
  - Poor reception
  - Slowly gets worse with distance
- F.M. Radio
  - Good reception
  - Catastrophically gets worse at critical distance
- This tends to be true for many highly structured systems
  - Congestion systems
  - Error correcting codes
  - The one horse shay

Distance vs. Quality chart for A.M. and F.M. Radio.
Simple 2-parameter Model For Delay

Delay $T$

Throughput

$T_0$

0

$\gamma^*$
Another application of Power
A Brief History of Radio

• Marconi 1890’s
A Brief History of Pkt Radio

- 1970’s: ARPA

- 250 cu in
- 25 watts
- 25 pounds

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A Brief History of Pkt Radio

• 1990’s: ARPA

10 cu in
1 watt
1 pound
Giant Stepping
in Packet Radio

- Multihop
- Each hop covers distance $R$ (Tx Radius)
- Total distance to cover is $D$ ($D \gg R$)
- Big $R$, more interference, fewer hops
- Small $R$, less interference, more hops
- Total Delay $= T(R)[D/R]$
- Choose $R = R^*$ to minimize total delay
- $dT(R)/dR = T(R)/R$ optimality condition

\[ \frac{dT(R)}{dR} = \frac{T}{R} \]

\[ T(R) \]

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The General Optimization Problem (1961 LK)

• Minimize

\[
T = \sum_{i} \frac{\lambda_i}{\gamma} T_i
\]

Channel Capacity Assignment
Routing Procedure
Message queueing discipline
Topology

• Subject to:

\[
D = \sum_{i} d_i C_i
\]

Where

\(C_i = \) Channel capacity of \(i^{th}\) channel
\(d_i = \) Cost to supply 1 unit of capacity to \(i^{th}\) channel
\(D = \) Total dollars available for design
Solution to the Problem

- Exact solution for $d_i = 1$
- Exact solution for arbitrary $d_i$
- Implications for topology
- Implications for routing procedure
- Implications for message sizes
The Underlying Principles

• Resource Sharing (demand access)
  • Only assign a resource to data that is present
  • Examples are:
    • Message switching
    • Packet switching
    • Polling
    • ATDM

• Economy of Scale in Networks

• Distributed control
  • It is efficient, stable, robust, fault-tolerant and WORKS!

Bursty Asynchronous Demands

- You cannot predict exactly **when** they will demand access
- You cannot predict **how much** they will demand
- Most of the time they **do not need** access
- When they ask for it, they want **immediate** access!!
Conflict Resolution

- **Queueing:**
  - One gets served
  - All others wait

- **Splitting:**
  - Each gets a piece of the resource

- **Blocking:**
  - One gets served
  - All others are refused

- **Smashing:**
  - Nobody gets served!
Resource Sharing

Type 0

Type 1

Type 2

A Fancy Green Switch
The Law of Large Numbers
(The First Resource Sharing Principle)

- Although each member of a large population may behave in a random fashion, the population as a whole behaves in a predictable fashion.
- This predictable fashion presents a total demand equal to the sum of the average demands of each member.
- This is the “smoothing effect” of large populations.
Resource Sharing

Type 0

Type 1

Type 2

Type 3

A Fancy Green Switch
The Economy of Scale
(The Second Resource Sharing Principle)

• If you scale up throughput and capacity by some factor F, then you reduce response time by that same factor.

• If you scale capacity more slowly than throughput while holding response time constant, then efficiency will increase (and can approach 100%).
Key Tradeoff: Response Time, Throughput, Efficiency

- Response Time Improving
- Throughput Increasing
- Efficiency Improving

- Constant Response Time
- Throughput Increasing
- Efficiency Improving

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Economy of Scale in Networks

Throughput

$/$/Kbps

Locus of Network Designs

Large Net

Small Net

Slope = Kbps/$

Cost

Throughput

Small Net

Large Net

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### Key System Parameter

\[ a = \text{Propag Delay/Pkt Tx Time} \]

\[ = 5LC/b \text{ (# packets in cable)} \]

- \( a = \text{Bandwidth (megabits/sec)} \)
- \( L = \text{Cable Length (kilometers)} \)
- \( PD = 5L \text{ (microseconds)} \)

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<th>PROP DELAY MICROSEC</th>
<th>LATENCY a</th>
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Conclusions

- Flow control is needed and tough
- Look for principles
- Be aware of prior work
- Don’t fall in love with your model
Thank You

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