Creating The Internet Technology

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SIGCOMM Tutorial
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My Early Years at MIT by Leonard Kleinrock

- 1959  Decided to pursue PhD, but decided NOT to work in Coding Theory, but rather set out to uncover the principles of data networks
- 1961  Published PhD Proposal: 1st paper on modern data networking
- 1962  Filed PhD Dissertation; MIT + McGraw-Hill decide to publish it as a book
- 1963  Joined UCLA faculty
- 1960’s Telecom industry could care less!
- 1966  ARPA gets interested
- 1969+ The network locomotive starts its wild ride
Information Flow in Large Communication Nets

Leonard Kleinrock

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Information Flow in Large Communication Nets
Proposal for a Ph.D. Thesis

Leonard Kleinrock

I. Statement of the Problem:

The purpose of this thesis is to investigate the problems associated with information flow in large communication nets. These problems appear to have wide application, and yet, little serious research has been conducted in this field. 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. The links consist of one-way channels, with fixed capacities. Among the typical systems which fit this description are the Post Office System, telegraph systems, and satellite communication systems.

A number of interesting and important questions can be asked about this system, and it is the purpose of this research to investigate the answers to some of these questions. A partial list of such questions might be as follows:

1. What is the probability density distribution for the total time lapse between the initiation and reception of a message between any two nodes? In particular, what is the expected value of this distribution?
2. Can one discuss the effective channel capacity between any two nodes?
3. Is it possible to predict the transient behavior and recovery time of the net under sudden changes in the traffic statistics?
4. How large should the storage capacity be at each node?
5. In what way does one arrive at a routing doctrine for incoming messages in different nets? In fact, can one state some bounds on the optimum performance of the net, independent of the routing doctrine (under some constraint on the set of allowable doctrines)?
“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....”

The counters to some of these questions is pursued here. Some questions might be as follows:

1. What is the probability density of the total time interval? What is the distribution?

2. Can one discuss the effective channel capacity, any two nodes?

3. Is it possible to predict the transient behavior of the net under question?

4. Should the capacity be at each node?

5. In what way does one design a routing doctrine for incoming messages in different nodes? Depends on the optimum performance of the doctrine (under some conditions...)

Time lapse between initiation and reception
Channel capacity
Storage capacity size
Transient behavior and recovery time
Routing doctrine
Under what conditions does the net jam up, i.e., present an excessive delay in transmitting messages through the net? The solution to this problem will dictate the extent to which the capacity of each link can be used (i.e., the ratio of rate to channel capacity, which is commonly known as the utilization factor).

What are the effects of such things as additional inter-node delays, and priority messages?

One other variable in the system is the amount of information that each node has about the state of the system (i.e., how long the queues are in each other node). It is clear that these are critical questions which need answers, and it is the intent of this research to answer some of them.

In attempting the solution of some of these problems, it may well be that the study of a specific system or application will expose the basis for an understanding of the problem. It is anticipated that such a study, as well as a simulation of the system on a digital computer, will be undertaken in the course of this research.

II. History of the Problem

The application of Probability Theory to problems of telephone traffic represents the earliest area of investigation related to the present communication network problem. The first work in this direction dates back to 1907 and 1908 when H. Johannsen [1],[2] published two essays, the one dealing with delays to incoming calls in a manual telephone exchange, and the other being an investigation as to how often subscribers with one or more lines are reported "busy." It was W. Johannsen who encouraged A.K. Erlang to investigate problems of this nature. Erlang, an engineer with the Copenhagen telephone exchange, made a number of major contributions to the theory of telephone traffic, all of which are translated and reported in [1]; his first paper (on the Poissonian distribution of incoming calls) appeared in 1909 and the paper containing the results of his main work was published in 1917, in which

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*References to Johannsen's work will be found in [1], page 16.
Under what conditions does the net jam up?
My Early Dissertation Work

- Developed theory of stochastic flow of message traffic in connected networks of communication centers:
  - Channel capacity limited
  - Mean response time as key metric
  - Optimal assignment of channel capacity
  - Choice of priority queueing discipline
  - Choice of routing procedure
  - Design of topological structure
- Developed underlying principles of data networks
Systems of Flow

- Steady flow through a single channel
  - Trivial and deterministic
- Unsteady flow through a single channel
  - Queueing theory; stochastics get you
- Steady flow through a network of channels
  - Network flow theory; multicommodity gets you
- 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 Results in My PhD Dissertation

- **Set up the model:**
  - Use of queueing theory; Erlang’s heritage
  - Independence assumption (critical!)
- **Evaluated network performance**
- **Developed optimal design procedures**
  - Capacity, topology, routing, message size
- **Introduced and evaluated distributed adaptive routing control**
- **Evaluated different queueing disciplines for handling traffic in the nodes, specifically, chopping messages into smaller segments**
Key Equation for Networks

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

This is EXACT!!

\[ T = \text{Average network delay} \]
\[ \lambda_i = \text{Traffic on channel i (Msg/sec)} \]
\[ \gamma = \text{Network throughput (Msg/sec)} \]
\[ T_i = \text{Average delay for channel i} \]

But how do you find this term?
Key Assumption

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.
The Independence Assumption

- 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)
Response Time vs Throughput

Response Time

Throughput

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How Do Queues Form?

\[ T = Nx + x \]

\[ N = \gamma T \] (Little’s Law)

\[ T = T\gamma x + x \]

\[ T = \frac{x}{1-\gamma x} \]

Throughput

Response Time

0 Throughput

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Simple 2-parameter Model
For Delay

Delay $T$

$T_0$

Throughput $\gamma^*$

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The General Optimization Problem

- **Minimize**  \[ T = \sum_{i} \frac{\lambda_i}{\gamma} T_i \]
- **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!
• A **Resource** is a device that can do work for you at a finite rate

• **Examples:**
  • A Communication Channel
  • A Computer
Resources
Demands

- A **Demand** requires work from resources

- **Examples:**
  - Packets (require transmission)
  - Jobs (require processing)
Demands
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!!
Resource Sharing
Type 0

Ooops!

Chaos!
Resource Sharing
Type 1
Dedicated Resources

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Resource Sharing
Type 2
Shared Resources

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: Telephone Trunks

Buildings @ \( \frac{2}{3} \) Erlangs

<table>
<thead>
<tr>
<th>Trunks</th>
<th>Blocking</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Trunk</td>
<td>40%</td>
</tr>
<tr>
<td>4 Trunks</td>
<td>17%</td>
</tr>
</tbody>
</table>

\( \frac{2}{3} \) Erlangs

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Resource Sharing: Telephone Trunks

64(2/3) Erlangs

64 Trunks

16(2/3) Erlangs

16 Trunks

22

16

2

1

2

1

2

0.05%

3%

Blocking

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Resource Sharing

Type 2

Shared Resources

A Fancy Green Switch
Resource Sharing
Type 3
LARGE Shared Resources

A Fancy Green Switch
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!
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%).
Resource Sharing: Data Communications

\[ T(B, C) = \frac{T(NB, NC)}{N} \]

- B: Blocks/sec
- C: Bits/sec
- NB: Blocks/sec
- NC: Bits/sec
Key Tradeoff:
Response Time, Throughput, Efficiency

- Response Time Improving
- Throughput Increasing
- Efficiency Improving

Response Time Improving, Throughput Increasing, Constant Efficiency

Constant Response Time
Throughput Increasing
Efficiency Improving

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Economy of Scale in Networks

Throughput

Cost

$/Kbps

Locus of Network Designs

Slope = Kbps/$

Small Net

Large Net

Small Net

Large Net

Throughput

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Thank You

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