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A Framework for Defining Network Complexity  
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#### Abstract

Complexity is a widely used parameter in network design, yet there is no generally accepted definition of the term. Complexity metrics exist in a wide range of research papers, but most of these address only a particular aspect of a network, for example the complexity of a graph or software. There is a desire to define the complexity of a network as a whole, as deployed today to provide Internet services. This document provides a framework to guide research on the topic of network complexity.

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## 1. Introduction

During the design phase of a network complexity plays a key role. Network designers generally seek to find the simplest design that fulfills a set of requirements. As no objective definition of network complexity exists, subjective measures are used to come to a conclusion. The resulting diverging views on what constitutes complexity subsequently lead to conflicts in design teams. While most people would agree that complexity is an important factor in network design, today's design decisions are made based on a rough estimation of the network's complexity, rather than a solid understanding.

The goal of this document is to define a framework for network complexity research. This framework describes related research and current understanding of the topic, as well as outlining some ways research could be taken forward. Specifically, contributions are invited in all of the areas mentioned.

Many references to existing research in the area of network complexity are listed on the Network Complexity Wiki [wiki]. This wiki also contains background information on previous meetings on the subject, previous research, etc.

## 2. General Considerations

### 2.1. The Behavior of a Complex Network

While there is no generally accepted definition of network complexity, there is some understanding of the behavior of a complex network. It has some or all of the following properties:

- o Self-Organization: A network runs some protocols and processes without external control; for example a routing process, failover mechanisms, etc. The interaction of those mechanisms can lead to a complex behaviour.
- o Un-predictability: In a complex network, the effect of a local change on the behaviour of the global network may be unpredictable.
- o Emergence: A network has an emergent property if a small local change produces a large scale, seemingly unrelated state or result.
- o Non-linearity: An input into the network produces a non-linear result.

- o Fragility: A small local input can break the entire system.

## 2.2. Robust Yet Fragile

Networks typically follow the "robust yet fragile" paradigm: They are designed to be robust against a set of failures, yet they are very vulnerable to other failures. Doyle [Doyle] explains the concept with an example: The Internet is robust against single component failure, but fragile to targeted attacks. The "robust yet fragile" property also touches on the fact that all network designs are necessarily making trade-offs between different design goals. The simplest one is articulated in "The Twelve Networking Truths" RFC1925 [RFC1925]: "Good, Fast, Cheap: Pick any two (you can't have all three)." In real network design, trade-offs between many aspects have to be made, including, for example, issues of scope, time and cost in the network cycle of planning, design, implementation and management of a network platform. Tradeoff between various parameters are discussed in section 3.

## 2.3. The Complexity Cube

Complex tasks on a network can be done in different components of the network. For example, routing can be controlled by central algorithms, and the result distributed (e.g., OpenFlow model); the routing algorithm can also run completely distributed (e.g., routing protocols such as OSPF or ISIS), or a human operator could calculate routing tables and statically configure routing. Behringer [Behringer] defines these three axes of complexity as a "complexity cube" with three axes: Network elements, central systems, and human operators. While different functions can be shifted between these axes of the network, the overall complexity may change.

## 2.4. Related Concepts

When discussing network complexity, a large number of influencing factors have to be taken into account to arrive at a full picture, for example:

- o State in the network: Contains the network elements, such as routers, switches (with their OS, including protocols), lines, central systems, etc. The number and algorithmical complexity of the protocols on network devices for example.
- o Human operators: Complexity manifests itself often by a network that is not completely understood by human operators. Human error is a primary source for catastrophic failures, and therefore must be taken into account.

- o Classes / templates: Rather than counting the number of lines in a configuration, or the number of hardware elements, more important is the number of classes from which those can be derived. In other words, it is probably less complex to have 1000 interfaces which are identically configured than 5 that are completely different configured.
- o Dependencies and interactions: The number of dependencies between elements, as well as the interactions between them has influence on the complexity of the network.
- o TCO (Total cost of ownership): TCO could be a good metric for network complexity, if the TCO calculation takes into account all influencing factors, for example training time for staff to be able to maintain a network.
- o Benchmark Unit Cost is a related metric that indicates the cost of operating a certain component. If calculated well, it reflects at least parts of the complexity of this component. Therefore, the way TCO or BUC are calculated can help to derive a complexity metric.
- o Churn / rate of change: The change rate in a network itself can contribute to complexity, especially if a number of components of the overall network interact.

Networks differ in terms of their intended purpose (such as is found in differences between enterprise and public carriage network platforms, and in their intended role (such as is found in the differences between so-called "access" networks and "core" transit networks). The differences in terms of role and purpose can often lead to differences in the tolerance for, and even the metrics of, complexity within such different network scenarios. This is not necessarily a space where a single methodology for measuring complexity, and defining a single threshold value of acceptability of complexity, is appropriate.

## 2.5. Technical Debt

Many changes in a network are made with a dependency on the existing network. Often, a suboptimal decision is made because the optimal decision is hard or impossible to realise at the time. Over time, the number of suboptimal changes in themselves cause significant complexity, which would not have been there had the optimal solution been implemented.

The term "technical debt" refers to the accumulated complexity of sub-optimal changes over time. As with financial debt, the idea is

that also technical debt must be repaid one day by cleaning up the network or software.

## 2.6. Layering considerations

In considering the larger space of applications, transport services, network services and media services, it is feasible to engineer responses for certain types of desired applications responses in many different ways, and involving different layers of the so-called network protocol stack. For example, quality of Service could be engineered at any of these layers, or even in a number of combinations of different layers.

Considerations of complexity arise when mutually incompatible measures are used in combination (such as error detection and retransmission at the media layer in conjunction with the use TCP transport protocol), or when assumptions used in one layer are violated by another layer. This results in surprising outcomes that may result in complex interactions. This has lead to the perspective that increased layering frequently increases complexity [RFC3439].

While this research work is focussed network complexity, the interactions of the network with the end-to-end transport protocols, application layer protocols and media properties are relevant considerations here.

## 3. Tradeoffs

>[I-D.irtf-ncrg-network-design-complexity] describes a set of trade-offs in network design to illustrate the practical choices network operators have to make. The amount of parameters to consider in such tradeoff scenarios is very large, thus that a complete listing may not be possible. Also the dependencies between the various metrics itself is very complex and requires further study. This document attempts to define a methodology and an overall high level structure.

To analyse tradeoffs it is necessary to formalise them. The list of parameters for such tradeoffs is long, and the parameters can be complex in themselves. For example, "cost" can be a simple unidimensional metric, but "extensibility" or "optimal forwarding state" are harder to define in detail.

A list of parameters to trade off contains metrics such as:

- o Cost: How much does the network cost to build (capex) and run (opex)

- o Bandwidth / delay / jitter: Traffic characteristics between two points (average, max, ...)
- o Configuration complexity: How hard to configure and maintain the configuration
- o Susceptibility to Denial-of-Service: How easy is it to attack the service
- o Security (confidentiality / integrity): How easy is it to sniff / modify / insert the data flow
- o Scalability: To what size can I grow the network / service
- o Extensibility: Can I use the network for other services in the future?
- o Ease of troubleshooting: How hard is it to find and correct problems?
- o Predictability: If I change a parameter, what will happen?
- o Clean failure: When a problem arises, does the root cause lead to deterministic failure

The list of the above criteria can be seen as forming an n-dimensional design space, where each network is represented in one intersection of all parameters.

#### 4. Structural Complexity

tbc

#### 5. Components of Complexity

Complexity can be found in various components of a networked system. For example, the configuration of a network element reflects some of the complexity contained in this system. Or an algorithm used by a protocol may be more or less complex. When classifying complexity the first question to ask is "WHAT is complex?". This section offers a method to answer this question.

##### 5.1. The Physical Network (Hardware)

tbc

##### 5.2. State in the Network

tbc

### 5.3. Churn

The frequency of change in a network intuitively contributes to its complexity: A network which is not subjected to change tends to be more stable [need ref here]. While there is permanently a certain base complexity in the network, this complexity is "under control" and does not lead to negative side effects.

[I-D.sircar-complexity-entropy] describes how entropy metrics can be used to describe changing complexity in a network. The fundamental thesis is that change itself constitutes complexity. When a network undergoes change, the network entropy and the complexity increases. This is also true when the change has simplification as a goal. The entropy increases during change, and decreases in periods of stability. It can therefore be used to measure the impact of change on complexity.

### 5.4. Algorithms

tbc

## 6. Location of Complexity

The previous section discussed in which form complexity may be perceived. This section focuses on where this complexity is located in a network. For example, an algorithm can run centrally, distributed, or even in the head of a network administrator. In classifying the complexity of a network, the location of a component may have an impact on overall complexity. This section offers a methodology to the question "WHERE is the complex component?"

### 6.1. Topological Location

tbc

### 6.2. Logical Location

tbc

### 6.3. Layering Considerations

tbc

## 7. Dependencies

Dependencies are generally regarded as related to overall complexity. A system with less dependencies is generally considered less complex. This section proposes a way to analyse dependencies in a network.

For example, [Chun] states: "We conjecture that the complexity particular to networked systems arises from the need to ensure state is kept in sync with its distributed dependencies."

In this document we distinguish three types of dependencies: Local dependencies, network wide dependencies, and network external dependencies.

#### 7.1. Local Dependencies

tbc

#### 7.2. Network Wide Dependencies

tbc

#### 7.3. Network External Dependencies

tbc

### 8. Management Interactions

A static network generally is relatively stable; conversely, changes introduce a degree of uncertainty and therefore need to be examined in detail. Also, the trouble shooting of a network exposes intuitively the complexity of the network. This section proposes a methodology to classify management interactions with regard to their relationship to network complexity.

#### 8.1. Configuration Complexity

tbc

#### 8.2. Troubleshooting Complexity

tbc

#### 8.3. Monitoring Complexity

tbc

#### 8.4. Complexity of System Integration

tbc

## 9. External Interactions

The user experience of a network also illustrates a form of complexity. A network can expose certain tasks to the user, or deal with them internally, hidden to the user. This section describes how user interactions can be analysed to expose complexity.

### 9.1. User Interactions

tbc

### 9.2. Interactions on End Systems

tbc

### 9.3. Inter-Network Interactions

tbc

## 10. Examples

In the foreseeable future it is unlikely to define a single, objective metric that includes all the relevant aspects of complexity. In the absence of such a global metric, a comparative approach could be easier.

For example, it is possible to compare the complexity of a centralised systems where algorithms run centrally, and the results are distributed to the network nodes with a distributed algorithm. The type of algorithm may be similar, but the location is different, and a different dependency graph would result. The supporting hardware may be the same, thus could be ignored for this exercise. Also layering is likely to be the same. The management interactions though would significantly differ in both cases.

The classification in this document also makes it easier to survey existing research with regards to which area of complexity is covered. This could help in identifying open areas for research.

## 11. Security Considerations

This document does not discuss any specific security considerations.

## 12. Acknowledgements

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