Networking and Communication (NC)

Preamble

Networking and communication play a central role in interconnected computer systems that are transforming the daily lives of billions of people. The public Internet provides connectivity for networked applications that serve ever-increasing numbers of individuals and organizations around the world. Complementing the public sector, major proprietary networks leverage their global footprints to support cost-effective distributed computing, storage, and content delivery. Advances in satellite networks expand connectivity to rural areas. Device-to-device communication underlies the emerging Internet of things.

This knowledge area deals with key concepts in networking and communication, as well as their representative instantiations in the Internet and other computer networks. Beside the basic principles of switching and layering, the area at its core provides knowledge on naming, addressing, reliability, error control, flow control, congestion control, domain hierarchy, routing, forwarding, modulation, encoding, framing, and access control. The area also covers knowledge units in network security and mobility, such as security threats, countermeasures, device-to-device communication, and multihop wireless networking. In addition to the fundamental principles, the area includes their specific realization in the Internet as well as hands-on skills in implementation of networking and communication concepts. Finally, the area comprises emerging topics such as network virtualization and quantum networking.

As the main learning outcome, learners develop a thorough understanding of the role and operation of networking and communication in networked computer systems. They learn how network structure and communication protocols affect behavior of distributed applications. The area educates on not only key principles but also their specific instantiations in the Internet and equips the student with hands-on implementation skills. While computer-system, networking, and communication technologies are advancing at a fast pace, the gained fundamental knowledge enables the student to readily apply the concepts in new technological settings.

Changes since CS 2013

Compared to the 2013 curricula, the knowledge area broadens its core tier-1 focus from the introduction and networked applications to include reliability support, routing, forwarding, and single-hop communication. Due to the enhanced core, learners acquire a deeper understanding of the impact that networking and communication have on behavior of distributed applications. Reflecting the increased importance of network security, the area adds a respective knowledge unit as a new elective. To track the advancing frontiers in networking and communication knowledge, the area replaces the elective unit on social networking with a new elective unit on emerging topics, such as middleboxes, software defined networks, and quantum networking.

Other changes consist of redistributing all topics from the old unit on resource allocation among other units, in order to resolve the unnecessary overlap between the knowledge units in the 2013 curricula.

Core Hours

Knowledge Units	CS Core	KA Core
Introduction	3	
Networked Applications	4	
Reliability Support		6
Routing And Forwarding		4
Single-Hop Communication		3
Mobility Support		4
Network Security		3
Emerging Topics		4
Total	**7**	**24**

Knowledge Units

NC-Introduction

CS Core:

1. Importance of networking in contemporary computing, and associated challenges. (See also: SEP-Social Context SEP-Privacy and Civil Liberties)
2. Organization of the Internet (e.g. users, Internet Service Providers, autonomous systems, content providers, content delivery networks).
3. Switching techniques (e.g., circuit and packet).
4. Layers and their roles (application, transport, network, datalink, and physical).
5. Layering principles (e.g. encapsulation and hourglass model).
6. Network elements (e.g. routers, switches, hubs, access points, and hosts).
7. Basic queueing concepts (e.g. relationship with latency, congestion, service levels, etc.)

Learning Outcomes:

1. Articulate the organization of the Internet.
2. List and define the appropriate network terminology.
3. Describe the layered structure of a typical networked architecture.
4. Identify the different types of complexity in a network (edges, core, etc.).

NC-Networked-Applications

CS Core:

1. Naming and address schemes (e.g. DNS, and Uniform Resource Identifiers).
2. Distributed application paradigms (e.g. client/server, peer-to-peer, cloud, edge, and fog). (See also: PDC-Communication, PDC-Coordination)
3. Diversity of networked application demands (e.g. latency, bandwidth, and loss tolerance). (See also: PDC-Communication, SEP-Sustainability)
4. An explanation of at least one application-layer protocol (e.g. HTTP).
5. Interactions with TCP, UDP, and Socket APIs. (See also: PDC-Programs and Execution)

Illustrative Learning Outcomes:

1. Define the principles of naming, addressing, resource location.
2. Analyze the needs of specific networked application demands. SEP-Social Context
3. Describe the details of one application layer protocol. .
4. Implement a simple client-server socket-based application.

NC-Reliability-Support

KA Core:

1. Unreliable delivery (e.g. UDP).
2. Principles of reliability (e.g. delivery without loss, duplication, or out of order).
3. Error control (e.g. retransmission, error correction).
4. Flow control (e.g. stop and wait, window based).
5. Congestion control (e.g. implicit and explicit congestion notification).
6. TCP and performance issues (e.g. Tahoe, Reno, Vegas, Cubic).

Illustrative Learning Outcomes:

1. Describe the operation of reliable delivery protocols.
2. List the factors that affect the performance of reliable delivery protocols.
3. Describe some TCP reliability design issues.
4. Design and implement a simple reliable protocol.

NC-Routing-and-Forwarding

KA Core:

1. Routing paradigms and hierarchy (e.g. intra/inter domain, centralized and decentralized, source routing, virtual circuits, QoS).
2. Forwarding methods (e.g. forwarding tables and matching algorithms).
3. IP and Scalability issues (e.g. NAT, CIDR, BGP, different versions of IP).

Learning Outcomes:

1. Describe various routing paradigms and hierarchies.

2. Describe how packets are forwarded in an IP network.
3. Describe how the Internet tackles scalability challenges. .

NC-Single-Hop-Communication

KA Core:

1. Introduction to modulation, bandwidth, and communication media.
2. Encoding and Framing.
3. Medium Access Control (MAC) (e.g. random access and scheduled access).
4. Ethernet and WiFi.
5. Switching (e.g. spanning trees, VLANS).
6. Local Area Network Topologies (e.g. data center, campus networks).

Illustrative Learning Outcomes:

1. Describe some basic aspects of modulation, bandwidth, and communication media.
2. Describe in detail on a MAC protocol.
3. Demonstrate understanding of encoding and framing solution tradeoffs.
4. Describe details of the implementation of Ethernet
5. Describe how switching works
6. Describe one kind of a LAN topology

NC-Network-Security

KA Core:

1. General intro about security (Threats, vulnerabilities, and countermeasures). (See also: SEP-Security, SEC-Foundations)
2. Network specific threats and attack types (e.g., denial of service, spoofing, sniffing and traffic redirection, man-in-the-middle, message integrity attacks, routing attacks, ransomware, and traffic analysis) (See also: SEC-Foundations)
3. Countermeasures (See also: SEC-Foundations, SEC-Cryptography)
   o Cryptography (e.g. SSL, TLS, symmetric/asymmetric).
   o Architectures for secure networks (e.g., secure channels, secure routing protocols, secure DNS, VPNs, DMZ, Zero Trust Network Access, hyper network security, anonymous communication protocols, isolation)
   o Network monitoring, intrusion detection, firewalls, spoofing and DoS protection, honeypots, tracebacks, BGP Sec, RPKI.

Illustrative Learning Outcomes:

1. Describe some of the threat models of network security.
2. Describe specific network-based countermeasures.
3. Analyze various aspects of network security from a case study.

NC-Mobility

KA Core:

1. Principles of cellular communication (e.g. 4G, 5G).
2. Principles of Wireless LANs (mainly 802.11).
3. Device to device communication.
4. Multihop wireless networks. (e.g. ad hoc networks, opportunistic, delay tolerant).

Illustrative Learning Outcomes:

1. Describe some aspects of cellular communication such as registration.
2. Describe how 802.11 supports mobile users.
3. Describe practical uses of device to device communication, as well as multihop.
4. Describe one type of mobile network such as ad hoc.

NC-Emerging-topics

KA Core:

1. Middleboxes (e.g. filtering, deep packet inspection, load balancing, NAT, CDN).
2. Network Virtualization (e.g. SDN, Data Center Networks).
3. Quantum Networking (e.g. Intro to the domain, teleportation, security, Quantum Internet).
4. Satellite, mmWave, Visible Light.

Illustrative Learning Outcomes:

1. Describe the value of middleboxes in networks.
2. Describe the importance of Software Defined Networks
3. Describe some of the added value achieved by using Quantum Networking

Professional Dispositions

● Meticulous: In meeting being able to design networks and communication systems.

● Collaborative: Working in groups to achieve a common objective.

● Proactive: Anticipating changes in needs and acting upon them.

● Professional: Complying to the needs of the community in a responsible manner.

● Responsive: Acting swiftly to changes in needs.

● Adaptive: Making the required changes happen when needed.

Math Requirements

Required:

● Probability and Statistics

- Discrete Math
- Simple queuing theory concepts.
- Fourier and trigonometric analysis for physical layer.

Shared Topics and Crosscutting Themes

Topic 1: NC-Introduction -> SEP-Social-Context, SEP-Privacy, SEP-Civil-Liberties
Topic 2: NC-Networked-Applications -> PDC-Communication, PDC-Coordination
Topic 2: NC-Networked-Applications -> PDC-Communication, SEP-Sustainability
Topic 5: NC-Networked-Applications -> PDC-Programs and Execution
Topic 1: NC-Network-Security -> SEP-Security, SEC-Foundations
Topic 2: NC-Network-Security -> SEC-Foundations
Topic 3: NC-Network-Security -> SEC-Foundations, SEC-Cryptography

Course Packaging Suggestions

Coverage of the concepts of networking including but not limited to types of applications used by the network, reliability, routing and forwarding, single hop communication, security, and other emerging topics.

Note: both courses cover the same KU's but with different allocation of hours for each KU.

Introductory Course:
- NC-Emerging Topics (2 hours)
- NC-Introduction (9 hours)
- NC-Mobility Support (3 hours)
- NC-Networked Applications (12 hours)
- NC-Network Security (3 hours)
- NC-Reliability Support (6 hours)
- NC-Routing and Forwarding (4 hours)
- NC-Single-Hop Communication (3 hours)

Advanced Course:
- NC-Emerging Topics (6 hours)
- NC-Introduction (3 hours)
- NC-Mobility Support (5 hours)
- NC-Networked Applications (4 hours)
- NC-Network Security (5 hours)
- NC-Reliability Support (8 hours)
- NC-Routing and Forwarding (6 hours)

- NC-Single-Hop Communication (5 hours)

Competency Specifications

- **Task NC1:** Write a white paper to explain stakeholder needs of a given networked environment.
- **Competency statement:** Identify various stakeholders of a networked environment and explain their specific needs.
- **Competency area:** Systems
- **Competency unit:** Requirements / Documentation / Evaluation **Required knowledge areas and knowledge units:**
  - NC-Introduction
  - NC-Networked Applications
- **Required skill level:** Explain
- **Core level:**

- **Task NC2:** Evaluate multiple network architectures and network elements to meet needs.
- **Competency statement:** Identify various network architectures and associated network elements suitable for the problem at hand, and evaluate the most suitable approach to solve a given problem.
- **Competency area:** Systems / Application
- **Competency unit:** Requirements / Design / Documentation / Evaluation
- **Required knowledge areas and knowledge units:**
  - NC-Mobility
  - NC-Networked Applications
  - NC-Network Security
  - NC-Reliability Support
  - NC-Routing and Forwarding
- **Required skill level:** Explain / Evaluate
- **Core level:**

- **Task NC3:** Develop a model to abstract a networked environment.
- **Competency statement:** Use modeling techniques and tools to simplify a networked environment for subsequent development.
- **Competency area:** Systems / Application / Theory
- **Competency unit:** Requirements / Design / Documentation
- **Required knowledge areas and knowledge units:**
  - NC-Introduction

- ○ [NC](#)-Networked Applications
- **Required skill level:** Develop
- **Core level:**

- **Task NC4:** Develop a networking protocol.
- **Competency statement:** Design and implement networking protocols that satisfy specific requirements, including various constraints during usage e.g. a simple file transfer protocol.
- **Competency area:** Systems / Application
- **Competency unit:** Requirements / Design / Development / Testing / Deployment / Documentation / Evaluation / Maintenance / Improvement
- **Required knowledge areas and knowledge units:**
    - ○ [NC](#)-Networked Applications
    - ○ [NC](#)-Reliability Support
    - ○ [NC](#)-Routing and Forwarding
    - ○ [NC](#)-Single Hop Communication
- **Required skill level:** Develop
- **Core level:**

- **Task NC5:** Develop networked application.
- **Competency statement:** Design and implement networked applications that satisfy specific requirements, including various constraints during usage.
- **Competency area:** Software / Application
- **Competency unit:** Requirements / Design / Development / Testing / Deployment / Documentation / Evaluation / Maintenance / Improvement
- **Required knowledge areas and knowledge units:**
    - ○ [NC](#)-Mobility
    - ○ [NC](#)-Networked Applications
    - ○ [NC](#)-Network Security
- **Required skill level:** Develop
- **Core level:**

- **Task NC6:** Evaluate the performance of a network, in specific latency, throughput, congestion, and various service levels.
- **Competency statement:** Identify and evaluate various indicators of the performance of a network to suit specific needs.
- **Competency area:** Systems / Theory

- **Competency unit:** Evaluation
- **Required knowledge areas and knowledge units:**
  - [NC](#)-Networked Applications
  - [NC](#)-Routing and Forwarding
- **Required skill level:** Evaluate
- **Core level:**

- **Task NC7:** Defend the network from an ongoing distributed denial-of-service attack.
- **Competency statement:** Identify the presence of an active security threat, the related vulnerabilities, and activate suitable countermeasures to defend the network from an ongoing attack of the given kind.
- **Competency area:** Systems / Application
- **Competency unit:** Evaluation
- **Required knowledge areas and knowledge units (cross cutting):**
  - [NC](#)-Emerging Topics
  - [NC](#)-Introduction
  - [NC](#)-Networked Applications
  - [NC](#)-Network Security
  - [NC](#)-Reliability Support
  - [NC](#)-Routing and Forwarding
- **Required skill level:** Evaluate
- **Core level:**

- **Task NC8:** Identify gray failures in a datacenter network.
- **Competency statement:** Identify the presence of gray failures through multidimensional health monitoring.
- **Competency area:** Software / Systems / Application
- **Competency unit:** Evaluation
- **Required knowledge areas and knowledge units (cross cutting):**
  - [NC](#)-Emerging Topics
  - [NC](#)-Introduction
  - [NC](#)-Networked Applications
  - [NC](#)-Network Security
  - [NC](#)-Reliability Support
  - [NC](#)-Routing and Forwarding
- **Required skill level:** Evaluate
- **Core level:**

- **Task NC9:** Deploy and securely operate a network of wireless sensors.
- **Competency statement:** Configure and deploy a given set of sensors in a networked environment to meet a certain need, and be able to operate them in a secure way.
- **Competency area:** Systems / Application
- **Competency unit:** Develop
- **Required knowledge areas and knowledge units (cross cutting):**
  - NC-Mobility
  - NC-Single Hop Communication
- **Required skill level:** Evaluate
- **Core level:**

- **Task NC10:** Write a white paper to explain social, ethical, and professional issues governing the design and deployment of networked systems.
- **Competency statement:** Identify various stakeholders and how social, ethical, and professional issues how the design and deployment of a given networking will affect them.
- **Competency area:** Systems / Theory
- **Competency unit:** Evaluation, Management, Adaptation to social issues.
- **Required knowledge areas and knowledge units:**
  - NC-Introduction
  - SEP-Social Context
- **Required skill level: Evaluate**
- **Core level:**

Committee

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Appendix: Core Topics and Skill Levels

KA	KU	Topic	Skill	Core	Hours
NC	Introduction	● Importance of networking in contemporary computing, and associated challenges.	Explain	CS	3
		● Organization of the Internet ○ Users, ○ Internet Service Providers ○ Autonomous systems ○ Content providers ○ Content delivery networks	Explain		
		● Switching techniques ○ Circuit Switching ○ Packet Switching	Evaluate		
		● Layers and their roles. ○ Application ○ Transport ○ Network ○ Datalink ○ Physical	Explain		
		● Layering principles ○ Encapsulation ○ Hourglass model	Explain		
		● Network elements ○ Routers ○ Switches ○ Hubs ○ Access points ○ Hosts	Explain		
		● Basic queueing concepts ○ Relationship with latency ○ Relationship with Congestion ○ Relationship with Service levels	Explain		
NC	Networked Applications	● Naming and address schemes. ○ DNS ○ IP addresses ○ Uniform Resource Identifiers	Explain	CS	4

		● Distributed application paradigms
		  ○ Client/server
		  ○ Peer-to-peer
		  ○ Cloud
		  ○ Edge
		  ○ Fog
			Evaluate		

		● Diversity of networked application demands
		  ○ Latency
		  ○ Bandwidth
		  ○ Loss tolerance
			Explain		

		● Application-layer development using one or more protocols:
		  ○ HTTP
		  ○ SMTP
		  ○ POP3
			Develop		

		● Interactions with TCP, UDP, and Socket APIs.	Explain		

NC	Reliability Support	● Unreliable delivery
		  ○ UDP
		  ○ Other
			Explain		

		● Principles of reliability
		  ○ Delivery without loss
		  ○ Duplication
		  ○ Out of order
			Develop	KA	6

		● Error control
		  ○ Retransmission
		  ○ Error correction
			Evaluate		

		● Flow control
		  ○ Stop and wait
		  ○ Window based
			Develop		

		● Congestion control
		  ○ Implicit congestion notification
		  ○ Explicit congestion notification
			Explain		

		● TCP and performance issues
		  ○ Tahoe
		  ○ Reno
		  ○ Vegas
		  ○ Cubic
		  ○ QUIC
			Evaluate		

NC	Routing and Forwarding	● Routing paradigms and hierarchy ○ Intra/inter domain ○ Centralized and decentralized ○ Source routing ○ Virtual circuits ○ QoS	Evaluate	KA	4
		● Forwarding methods ○ Forwarding tables ○ Matching algorithms	Apply		
		● IP and Scalability issues ○ NAT ○ CIDR ○ BGP ○ Different versions of IP	Explain		
NC	Single Hop Communication	● Introduction to modulation, bandwidth, and communication media.	Explain	KA	3
		● Encoding and Framing.	Evaluate		
		● Medium Access Control (MAC) ○ Random access ○ Scheduled access	Evaluate		
		● Ethernet	Explain		
		● Switching	Apply		
		● Local Area Network Topologies (e.g. data center networks)	Explain		
NC	Network Security	● General intro about security [Shared with Security] ○ Threats ○ Vulnerabilities ○ Countermeasures	Explain	KA	4
		● Network specific threats and attack types [Shared with Security] ○ Denial of service ○ Spoofing ○ Sniffing ○ Traffic redirection ○ Man-in-the-middle ○ Message integrity attacks ○ Routing attacks	Explain		

		○ Traffic analysis			
		● Countermeasures [Shared with Security] ○ Cryptography (e.g. SSL, symmetric/asymmetric). ○ Architectures for secure networks (e.g., secure channels, secure routing protocols, secure DNS, VPNs, DMZ, Zero Trust Network Access, hyper network security, anonymous communication protocols, isolation) ○ Network monitoring, intrusion detection, firewalls, spoofing and DoS protection, honeypots, tracebacks, BGP Sec.	Explain		
NC	Mobility	● Principles of cellular communication (e.g. 4G, 5G)	Explain	KA	3
		● Principles of Wireless LANs (mainly 802.11)	Explain		
		● Device to device communication [Shared with SPD]	Explain		
		● Multihop wireless networks	Explain		
		● Examples (e.g ad hoc networks, opportunistic, delay tolerant)	Explain		
NC	Emerging Topics	● Middleboxes (e.g. filtering, deep packet inspection, load balancing, NAT, CDN)	Explain	KA	4
		● Virtualization (e.g. SDN, Data Center Networks)	Explain		
		● Quantum Networking (e.g. Intro to the domain, teleportation, security, Quantum Internet)	Explain		