NSWI090: **Computer Networks**

http://www.ksi.mff.cuni.cz/~svoboda/courses/242-NSWI090/

Lecture 8

Addressing

Martin Svoboda
martin.svoboda@matfyz.cuni.cz

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Charles University, Faculty of Mathematics and Physics

Lecture Outline

Addresses and addressing

- L2: **MAC** addresses
- L3: **IP** addresses
  - **IPv4 addresses**
    - Subnetting and supernetting
    - CIDR
    - Registries
    - Private addresses and NAT
  - **IPv6 addresses**
- L4: **port** numbers
- L7: **URI** identifiers

Addressing at L2

MAC addresses (**hardware addresses**)

- Used at L2
  - More precisely at the **MAC sublayer** (**Media Access Control**)
- Assigned to **network interface controllers**
  - I.e., individual L2 interfaces of end nodes as well as routers
  - Bridges / switches only have one MAC address, <u>if any</u>
    - In case they should explicitly be accessible as ordinary devices
    - Not because of fulfilling their L2 tasks (filtering / forwarding)
- Types of addresses
  - Standard **unicast**, but also **multicast** and **broadcast**
- **Different technologies** may have different mechanisms
  - However, **sharing of address spaces** may be desirable
    - So that **Wi-Fi and Ethernet** can coexist in one network

Addressing at L2

MAC addresses (cont'd)

- Must be **locally unique** within a given network
  - So that senders can **identify** the intended recipients
  - And these recipients are able to **recognize** their frames
    - Since everything is / may be delivered to everyone
    - Because all nodes are mutually visible and reachable
- **Assignment strategies**
  - **Locally** administered addresses would suffice
  - However, **globally unique addresses** simplify everything
    - Otherwise newly connected devices would need to be treated
    - So that they do not potentially use conflicting addresses
- $\Rightarrow$ **globally** unique **burned-in** addresses **assigned by device manufacturers** are primarily used in practice
  - Exceptions exist, though

EUI Addresses

EUI numbering systems (**Extended Unique Identifier**)

- **EUI-48** (48 bits, 6 bytes, $\approx$ 281 trillion addresses)
  - Formerly denoted as **MAC-48**
    - Which is inappropriate since MAC denotes the entire sublayer
    - And so this label should no longer be used since it is obsolete
  - **Notation**
    - Six hexadecimal numbers separated by hyphens or colons
    - E.g.: `FC-77-74-19-41-1E` or `FC:77:74:19:41:1E`
  - Deployment: **Ethernet**, **Wi-Fi**, **Bluetooth**, **ATM**, …
- **EUI-64** (64 bits, 8 bytes)
  - Newer version with larger address space
  - **Conversion** of EUI-48 possible by adding `FF-FE` in the middle
    - E.g.: `FC-77-74-FF-FE-19-41-1E`
  - Deployment: FireWire (IEEE 1394), …

EUI Addresses

Internal structure

- **Organizationally Unique Identifier** (**OUI**)
  - **Higher 3 bytes** (24 bits)
  - Describes a particular **vendor or manufacturer**
    - E.g.: `FC-77-74` (Intel), `90-F6-52` (TP-Link), …
- **Interface number**
  - Lower 3 bytes (24 bits) in case of EUI-48
  - Lower 5 bytes (40 bits) in case of EUI-64
  - **Serial number** of a given **network interface controller**

OUI Identifiers

OUI component details

- **M bit** (**I/G bit**) = the least significant bit of the first byte
  - 0 = **individual address** (unicast)
  - 1 = **group address** (multicast, broadcast)
- **X bit** (**U/L bit**) = the second least significant bit of the first byte
  - 0 = **Universally Administered Addresses** (UAA)
    - Intended for globally unique addresses
  - 1 = **Locally Administered Addresses** (LAA)
- Examples
  - **Individual** (M = 0) and **universal** (X = 0)
    - `FC-77-74-19-41-1E`: in binary `11111100-`…
  - **Group** (M = 1) and **local** (X = 1)
    - `FF-FF-FF-FF-FF-FF` (L2 broadcast): in binary `11111111-`…

OUI Identifiers

Observations

- Why M and X bits are the **two least significant bits**?
  - **Ethernet** uses **Big Endian** for the individual **bytes**
  - But **Little Endian** for individual **bits** within these bytes
    - Therefore the first two transmitted bits become M and X
    - And so various address modes can be distinguished easily
- Both M and X bits are **set to zeros** in **OUI identifiers** as such
  - Only when they are exploited in EUI addresses…
    - … they can then be changed as required and so their special meaning activated and utilized

OUI Identifiers

Organizationally Unique Identifier (**OUI**) (cont'd)

- Unique **vendor, manufacturer, or other organization** identifier
  - **Purchased** from the **IEEE Registration Authority**
  - One organization may actually have multiple OUIs at a time
- Various usages
  - Our **EUI-48 and EUI-64 addresses**
  - But also **SNAP Protocol Identifiers** (IEEE 802.2 LLC extension)
  - …
- **Online list**: http://standards-oui.ieee.org/oui/oui.txt
  - Current status (April 2021)
    - Almost 30 thousand OUIs are assigned
    - Huawei $\approx$ 1100, Cisco $\approx$ 1060, Apple $\approx$ 890, Samsung $\approx$ 690, …
    - TP-Link $\approx$ 160, Technicolor $\approx$ 80, D-Link $\approx$ 60, Zyxel $\approx$ 40, …
    - More than 17 thousand organizations only have a single OUI

Addressing at L3

IP addresses

- Primary objective is **addressing of nodes** as a whole
- In spite of that…
  - IP addresses are actually assigned to their **network interfaces**
  - I.e., individual L3 interfaces of end nodes as well as routers
    - Note that end nodes used to usually have only one IP address
    - But nowadays, **multi-homed** hosts with more IPs are common
- Another observation…
  - **<u>Routing algorithms perceive networks as a whole</u>**
  - $\Rightarrow$ **networks themselves** must also be **uniquely identified**
    - Though two separate network / node identifiers could work
    - **Internally structured atomic IP addresses** are more practical
  - Otherwise hop-to-hop **routing** and **forwarding** would not work

IP Addresses

Requirements on IP addresses

- **Globally unique** within the whole system of networks
- And internally structured…

Internal components

- **Network part** (**Network ID**)
  - **Prefix** of the whole address
    - I.e., certain part from the beginning
  - **Uniquely identifies a given network** as a whole
  - Determines affiliation of nodes to a particular network
- **Relative part** (**Host ID**)
  - Remaining part of the whole address
  - **Uniquely identifies a given node** within a given network

Assignment Principles

Observations = rules that must be followed

- **Two nodes in the same network**…
  - Must have the same network parts
  - And different relative parts
    - So that they can be mutually distinguished
- **Two nodes in different networks**…
  - Must have different network parts
    - So that we can detect they belong to different networks
  - And as for relative parts, they do not matter
    - They may be the same as well as not

Assignment Principles

Block principle

- (1) **network as a whole** must first be assigned with a whole contiguous **block of addresses**
  - I.e., set of IP addresses belonging to a specific range
    - All with the same prefix (network part)
  - **Assignment process** must be **globally coordinated**
    - **IANA and regional providers**
- (2) only than **individual nodes** can be given their addresses
  - Of course, from this range
  - Manually or using **DHCP or similar protocols**

Consequence

- **Unused addresses cannot be used by anyone else!**
  - This may lead / actually led to unacceptable wasting

IPv4 Addresses

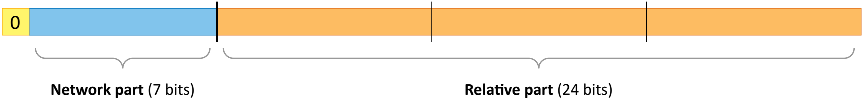
IPv4 addresses

- **4 bytes** (32 bits) – potentially $\approx$ 4 billion values
  - Which is certainly not much from today's perspective
    - But was initially thought of as generously sufficient
- **Notation**
  - Four decimal numbers, one for each byte, separated by dots
  - E.g.: 195.113.19.170
- **Internal structure**: **network and relative parts**
  - Where the divide between the parts should be located?
    - 3 possible **divide placements** are possible
    - This gives us **Classes A, B and C** of IP addresses
  - If more options exist, though, how to recognize them?
    - Since it must be possible just from the IP address itself

Classes of IPv4 Addresses

Class A

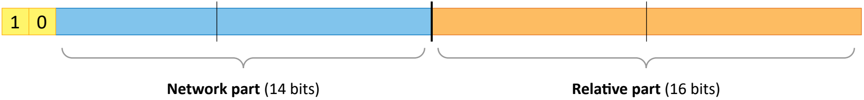
- Divide is positioned **after the first byte**
  - ≈ 128 networks
  - Each with ≈ 17 million addresses
- Overall **range**: **0**.0.0.0 – **127**.255.255.255
  - Covers 1/2 of the entire space
- **Highest bit** is 0
- Suitable for **very large networks**



Classes of IPv4 Addresses

Class B

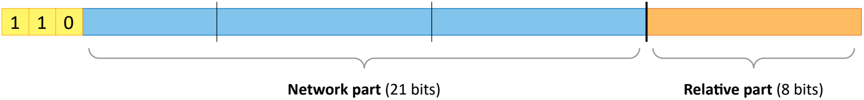
- Divide is positioned **after the second byte**
  - ≈ 16 thousand networks
  - Each with ≈ 66 thousand addresses
- Overall **range**: **128.0**.0.0 – **191.255**.255.255
  - Covers 1/4 of the entire space
- **Highest bits** are 10
- Suitable for **medium-sized networks**



Classes of IPv4 Addresses

Class C

- Divide is positioned **after the third byte**
  - ≈ 2 million networks
  - Each with ≈ 256 addresses only
- Overall **range**: **192.0.0**.0 – **223.255.255**.255
  - Covers 1/8 of the entire space
- **Highest bits** are 110
- Suitable for **very small networks**



Classes of IPv4 Addresses

Apparently the **available space** is not yet fully utilized…

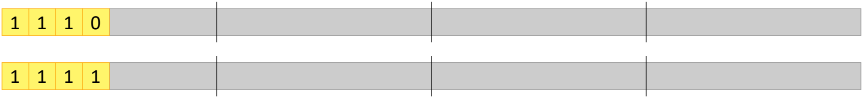
- The rest is covered by **Classes D and E**
  - They have **specific usage** and they are **internally unstructured**

Class D: **multicast addresses**

- 224.0.0.0 – 239.255.255.255 (1/16 of the entire space)
- Highest bits are `1110`

Class E: reserved for **future extensions**, but never used

- 240.0.0.0 – 255.255.255.255 (1/16 of the entire space)
- Highest bits are `1111`



Special Addresses

Special addresses

- Certain addresses (even whole ranges) have **dedicated usage**
  - Basic principle: bit 0 **= this**, bit 1 **= all**

Nodes

- Self node: **0.0.0.0**
  - Useful when standard unicast address is not yet known
- Node in a local network: **0**.X.Y.Z, **0.0**.X.Y, or **0.0.0**.X

Networks

- Network as a whole: X.**0.0.0**, X.Y.**0.0**, or X.Y.Z.**0**

Broadcasts

- **Targeted** broadcast: X.**255.255.255**, X.Y.**255.255**, or X.Y.Z.**255**
- **Limited** broadcast: **255.255.255.255**

Special Addresses

Loopback

- 1 A-block: **127**.X.Y.Z
  - **127.0.0.1** is in particular usually used
  - But the whole block is in fact available

Link local addresses

- 1 B-block: **169.254**.X.Y
  - Auto-configuration when standard address cannot be obtained

Private addresses

- 1 A-block: **10**.X.Y.Z
- 16 B-blocks: **172.16**.X.Y – **172.31**.X.Y
- 256 C-blocks: **192.168.0**.X – **192.168.255**.X

Multicast Addresses

Multicast transmissions

- Intended recipients are all nodes in a given group
  - This group is predefined or created dynamically on demand
    - **IGMP** (**Internet Group Management Protocol**)
- Certain blocks are assigned and approved by **IANA**
  - https://www.iana.org/assignments/multicast-addresses/
  - Current status (April 2021)
    - $\approx$ 60 static multicast addresses (beside other)
- **Class D addresses** are used
  - Start with 1110 and they are **internally unstructured**
    - I.e., there is no network / relative part

Multicast Addresses

Static groups (**well known** groups)

- Node membership is fixed and given in advance
- Range: 224.0.0.0 – 224.0.0.255 (≈ 256 addresses)
  - Reserved for **routing and other low-level protocols**
    - Topology discovery, maintenance, …
  - **224.0.0.1**: **all hosts** in a given network
  - **224.0.0.2**: **all routers** in a given network
  - …

Dynamic groups

- **Global**: 224.0.1.0 – 238.255.255.255 (≈ 252 million)
  - Group scope can span multiple different networks
- **Local**: 239.0.0.0 – 239.255.255.255 (≈ 17 million)
  - Group scope is limited to a particular network

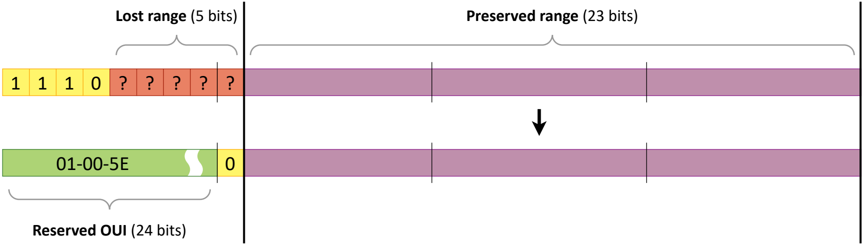
Multicast Addresses

Translation of multicast addresses (**IP** $\rightarrow$ **EUI-48**)

- L3 multicast **IP address**
  - 4 bits at the beginning are fixed $\Rightarrow$ only **28 bits are relevant**
  - Unfortunately, **only the last 23 bits** can be considered
    - And so the remaining 5 bits in the middle must be truncated
    - $\Rightarrow$ 32 different addresses are mapped to the same value!
- L2 multicast **EUI-48 address**
  - `00-00-5E` reserved **OUI** is used (24 bits)
    - Of course, altered to `01-00-5E` so that M bit = 1
  - The 25th bit is set to `0`
  - The remaining 23 bits are taken from the original IP address

Multicast Addresses

Translation of multicast addresses (**IP** $\rightarrow$ **EUI-48**) (cont'd)



Allocation Strategies

Basic principle

- **Whole blocks** of addresses are / must be assigned to networks
- These blocks correspond to our **classes**
  - One **Class A** block $\approx$ 17 million individual addresses
  - One **Class B** block $\approx$ 66 thousand individual addresses
  - One **Class C** block $\approx$ 256 individual addresses

Strategies

- Formerly: **one closest larger block principle**
  - E.g.: 1 Class B address for 1000 requested individual addresses
    - Extremely wasteful approach…
- Later: **multiple closest smaller blocks principle**
  - E.g.: just 4 Class C addresses for the same requested number
    - Better, but still not enough…

IPv4 Address Exhaustion

Temporary **mitigating solutions**

- 1985: **Subnetting**
  - One larger network is divided into separate sub-networks
- 1988: Allocation mechanism
  - **One larger block** $\rightarrow$ **more smaller blocks** principle
- 1993: **CIDR** (**Classless Inter-Domain Routing**)
  - Original concept of IP address classes is entirely dropped
- 1994: **Private addresses**
  - Usage of private IPv4 addresses instead of globally unique ones
  - Requires **NAT** (**Network Address Translation**)

Permanent solution

- 1995: IPv6 protocol and its **IPv6** **addresses**
  - **16 bytes** instead of 4 bytes $\Rightarrow$ significantly **larger address space**

Subnetting

Motivation

- **One closest larger block allocation principle** is used
- $\Rightarrow$ inner block address space may not be used efficiently
  - Since **unused addresses cannot be used by anyone else**
    - This in fact led to unacceptable wasting
- Objective
  - **Higher utilization of addresses** within allocated blocks

Principle

- **Division of larger blocks into smaller ones**
  - In terms of decomposition of networks into subnetworks

Subnetting

Subnetting

- Standard network is **internally divided into** **subnetworks**
  - Standard means Class A, B, or C block
- **Divide position is shifted to the right** (toward lower bits)
  - By one or more bits as needed
- $\Rightarrow$ **divide position** must be somehow remembered
  - Since the traditional class boundaries will no longer work
  - And we still must be able to recognize IP address parts
    - Which will now be impossible without extra information
- **Netmask** (**subnet mask**) was proposed for this purpose
  - Written as an ordinary IP address
    - Contains **bits** 1 in the intended **network part**, **bits** 0 elsewhere
  - E.g.: 255.255.0.0 as an equivalent of Class B network

Subnetting: Example

Assume we have a Class C **network** 195.113.19.0

- Permits ≈ 256 addresses, netmask would be 255.255.255.0

It can be divided into the following **subnetworks**

- Subnetwork 195.113.19.**0** with netmask 255.255.255.**128**
  - I.e., 195.113.19.**0**0000000$_B$, netmask 255.255.255.**1**0000000$_B$
  - **Divide shifted by +1**, allows ≈ 128 individual addresses
- Subnetwork 195.113.19.**128** with netmask 255.255.255.**192**
  - I.e., 195.113.19.**10**000000$_B$, netmask 255.255.255.**11**000000$_B$
  - **Divide shifted by +2**, allows ≈ 64 individual addresses
- Subnetwork 195.113.19.**192** with netmask 255.255.255.**192**
  - I.e., 195.113.19.**11**000000$_B$, netmask 255.255.255.**11**000000$_B$
  - **Divide shifted by +2**, allows ≈ 64 individual addresses

Subnetting

Observations

- Both **routers and end nodes** must support the whole concept
  - Which is not a big deal since…
    - We are the owners of the **infrastructure** within the network
    - **End nodes** can easily be adapted via software updates
- Subnetting is always **limited to a given standard network** only
  - Its **impact <u>must not be visible from outside</u>**
    - I.e., network as a whole still must act as an atomic unit
    - And so global routing and forwarding are not impacted at all

Supernetting

Motivation

- **More closest smaller blocks allocation principle** is used
- $\Rightarrow$ size of **routing tables** increases
  - Since **each individual network** must have its **own record**
  - Routing tables therefore became unacceptably large
    - As well as routing tables **lookup slowed down**
- Objective
  - **Reducing overall size of routing tables** in backbone routers
    - And so with no impact on depletion of IP addresses themselves

Principle

- **Aggregation of smaller blocks into larger ones**
  - In terms of records in routing tables

Supernetting

Supernetting (**Aggregation**)

- Several **adjacent aligned blocks are merged together**
  - They must share the same prefix of their network IDs
  - Entire address space defined by this prefix must be covered
  - All the original blocks must have the same routing direction
- **Divide position is shifted to the left** (toward higher bits)
- $\Rightarrow$ once again, **netmasks** are needed

Observations

- Supernetting is **entirely transparent**
  - Contrary to subnetting…
  - And so all **routers** within the system must support the concept

Supernetting: Example

Assume we have the following individual Class C **networks**

- Or just one network with the following address blocks…
  - Target network 195.113.**16**.0 (i.e., 195.113.000100**00**$_B$.0)
  - Target network 195.113.**17**.0 (i.e., 195.113.000100**01**$_B$.0)
  - Target network 195.113.**18**.0 (i.e., 195.113.000100**10**$_B$.0)
  - Target network 195.113.**19**.0 (i.e., 195.113.000100**11**$_B$.0)
- They all have the same routing direction

Their **routing records** can thus be grouped together

- Target network 195.113.**16**.0 with netmask 255.255.**252**.0
  - I.e., 195.113.**000100**00$_B$.0, netmask 255.255.**111111**00$_B$.0
  - **Divide shifted by -2**

Regional Registries

Original **arrangement**

- **Entire address space** was managed by IANA
  - I.e., individual blocks were **directly** assigned to **end users**
    - In terms of **Class A, B, or C blocks**
- Involved **agenda** became far too **extensive and demanding**
  - $\Rightarrow$ individual regional registries were gradually founded
    - And related agenda correspondingly transferred

Regional Internet Registry (**RIR**)

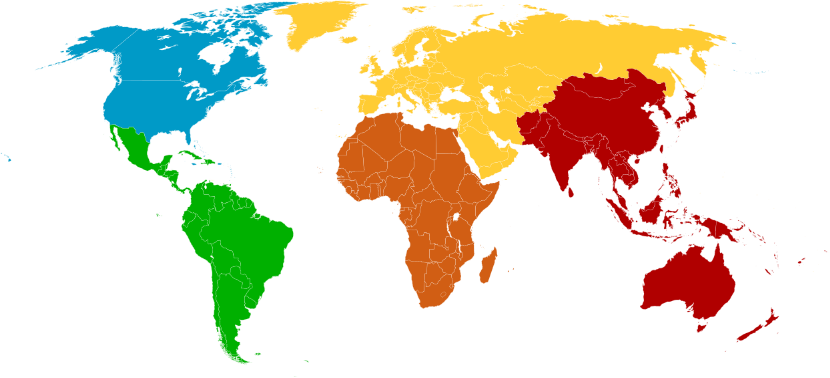
- **Organization** managing **allocation and registration** of Internet resources within a given region
  - **IP addresses** and **Autonomous System Numbers**
- **5 individual RIRs** around the world exist nowadays
  - Each obtains larger blocks of IP addresses from IANA

Regional Registries

Regional registries

- 1992: **RIPE NCC** (**Réseaux IP Européens Network Coordination Centre**)
  - Europe, Central Asia, Russia, West Asia
- 1993: **APNIC** (**Asia Pacific Network Information Centre**)
  - South, East, and Southeast Asia, Oceania
- 1997: **ARIN** (**American Registry for Internet Numbers**)
  - USA, Canada, Antarctica, …
  - Operating in fact since 1991
- 1999: **LACNIC** (**Latin America and Caribbean Network Information Centre**)
  - Latin America, Caribbean
- 2004: **AFRINIC** (**African Network Information Centre**)
  - Africa

Regional Registries



CIDR

Motivation

- **Allocation of address blocks is still not flexible enough**
  - Because of **coarse granularity** of possible block sizes
  - Especially for networks of **mid-sized organizations**
    - Class C with $\approx$ 256 addresses is too small
    - Class B with $\approx$ 66 thousand addresses is too large
- **Subnetting** and **supernetting** both helped…
  - But **transparent** solution is needed so that the **entire address space** can be exploited efficiently enough (not just parts of it)
- Objective
  - **Hierarchical allocation of address blocks with arbitrary sizes**
    - So that block sizes can better match projected needs
- Principle: **fully classless routing mechanism**

CIDR

CIDR (**Classless Inter-Domain Routing**)

- **Concept of classes** is now definitely abandoned
  - Except for Classes D (multicast addresses) and E (future use)
    - Their meaning and ranges were preserved untouched
    - Including the meaning of other special addresses
- **Divide can now be placed anywhere**
  - I.e., leading bits no longer determine anything
  - And so **divide position** must once again be explicitly declared
    - Though analogous to netmasks…
    - … different and more convenient notation was introduced
- **CIDR Prefix** (or simply **prefix**)
  - **Number of bits** forming the network part
    - Written as a decimal number after the slash symbol at the end
  - E.g.: 172.217.0.0/16 as an equivalent of former Class B network

CIDR: Example

Assume we have an **allocated block** 195.113.19.0/24

- It can internally be divided into the following networks
  - Network A: 195.113.19.**0**/**25** (i.e.,195.113.19.**0**0000000$_B$/**25**)
  - Network B: 195.113.19.**128**/**26** (i.e.,195.113.19.**10**000000$_B$/**26**)
  - Network C: 195.113.19.**192**/**26** (i.e.,195.113.19.**11**000000$_B$/**26**)

Detailed **routing information**…

- Can remain **entirely undisclosed**
  - 195.113.19.**0**/**24** for all our networks
- As well as intentionally **fully or partially exposed** if needed
  - 195.113.19.**0**/**25** for network A
  - 195.113.19.**128**/**25** for aggregated networks B and C

CIDR

Observations

- CIDR is **deployed globally** and **fully transparent**
  - I.e., its scope is not limited just to a particular internetwork
    - As was the case of subnetting alone
- Meaning of **former classes** can be preserved
  - Class A / B / C blocks correspond to CIDR prefixes 8 / 16 / 24
    - By the way, individual addresses have CIDR prefix 32
- However, they can also be **transparently decomposed**…
  - E.g., 172.217.23.0/24 is a CIDR block with prefix 24
    - I.e., it provides $\approx$ 256 individual addresses
    - As if it was just an ordinary Class C block
    - But it is not, since it is just a part of a former Class B block
    - Such a thing would not be possible without CIDR
- As a consequence, **entire address space is treated uniformly**

CIDR

Observations (cont'd)

- Ideas of both **subnetting and supernetting** are supported
  - **Larger blocks can be divided into smaller ones**
    - In terms of decomposition of networks
    - So that the **address space** can be utilized more efficiently
    - Because block sizes can be chosen with **finest granularity**
  - **Smaller blocks can be aggregated into larger ones**
    - In terms of grouping of routing records
    - So that size of **routing tables** can hopefully be reduced
    - And so detailed routing information can remain localized
    - Without needing it to be disseminated globally
- Allows for **hierarchical assignment of address blocks**
  - And so the whole hierarchy of registries
    - Which also helps with the growing **agenda**

Hierarchy of Registries

Hierarchy levels

- **CIR** (**Central Internet Registry**) = **IANA**
- **RIR** (**Regional Internet Registry**)
  - RIPE NCC, APNIC, ARIN as well as later on LACNIC and AFRINIC
  - Later on liaised through **NRO** (**Number Resource Organization**)
    - Informal body coordinating matters of global importance
- Optional **NIR** (**National Internet Registry**)
  - National allocators in **larger countries** only
    - **APNIC** region: China, India, Japan, Korea, Indonesia, …
    - **LACNIC** region: Brazil, Mexico
- **LIR** (**Local Internet Registry**)
  - **ISPs**, larger enterprises, or **academic institutions**
  - Membership in a given RIR / NIR is required

Allocation Mechanisms

Example: end node **195.113.19.170**

- **IANA**
  - 195.0.0.0/8 ($\approx$ 17 million addresses) $\rightarrow$ **RIPE NCC**
- RIR: **RIPE NCC**
  - 195.113.0.0/16 ($\approx$ 66 thousand addresses) $\rightarrow$ **Cesnet**
    - Autonomous System AS2852
  - 195.113.0.0/18 ($\approx$ 16 thousand) $\rightarrow$ **Charles University**
    - Publicly invisible as for routing records
- Internal invisible decomposition
  - …
  - 195.113.18.0/23 ($\approx$ 512 individual addresses)
- Target **end node**
  - 195.113.19.170/32 $\rightarrow$ nosql.ms.mff.cuni.cz

Allocation Mechanisms

Allocation process

- **IANA**
  - Delegates **/8 blocks** to individual RIRs
    - Certain blocks are assigned to particular organizations directly
    - E.g.: US Postal Service, US Department of Defense, …
  - **Online database**
    - https://www.iana.org/assignments/ipv4-address-space/
    - Contains only records for **/8 blocks**
- **RIRs / NIRs**
  - Delegate parts of allocated blocks to subordinated LIRs
- **LIRs**
  - Assign smaller blocks to **end users**
    - Often **singleton addresses** only
  - Consequence: **addresses became dependent** on particular LIRs

Allocation Mechanisms

IANA top level **database** for /8 blocks

- **Types** of records
  - **Allocated**
    - Delegated entirely to a specific RIR or other organization
  - **Legacy**
    - Formerly allocated by IANA prior to the foundation of RIRs
    - Later on transferred to and administered by individual RIRs
  - **Reserved**
    - Designated for **specific purposes** (e.g., loopback, …)
  - **Unallocated**
    - Not yet allocated or reserved and so **available** for assignment

Allocation Mechanisms

Current situation (May 2021)

- **Distribution of /8 blocks** between individual RIRs
  - ARIN (93), APNIC (50), RIPE NCC (40), LACNIC (10), AFRINIC (6)
  - Class D multicast addresses (16), Class E future use (16), …
- **Overall allocation of /8 blocks**
  - 2011: IANA delegated the very last available blocks
    - One to every individual of all 5 RIRs
  - $\Rightarrow$ there is **no longer any unallocated /8 block**
- Situation in **RIPE NCC**
  - 2019: the very last block from the pool was allocated
  - Only **recovered addresses** via a **waiting list** are now available
    - I.e., blocks returned by former LIR holders
    - Currently $\approx$ 320 thousand individual addresses available

Private Addresses

Motivation

- Each node must have a **globally unique IP address**
  - I.e., address distinct within the whole system of networks
    - Otherwise routing will not work
  - **Number of available addresses is still decreasing**, though
    - Despite all the other already discussed mitigating measures
- Idea
  - **Nodes in a private network** can use **private addresses** instead
  - These **private addresses will then be translated** to public ones
    - In order to ensure they do not leave a given private network
- Two basic translation mechanisms are available
  - **NAT** (**Network Address Translation**)
  - **L7 Gateways**

Private Addresses

Observations

- **Any range of addresses could theoretically be used**
  - However, it is not desirable and correct
  - In particular, when such addresses would (even accidentally) **leak out from a given private network**…
    - It will not be possible to remedy the situation later on
    - Simply because other routers will not be able to detect them
- Therefore **dedicated addresses** should be used
  - 1 Class A block: **10**.X.Y.Z
    - I.e., **10**.0.0.0/**8**
  - 16 Class B blocks: **172.16**.X.Y – **172.31**.X.Y
    - I.e., **172.16**.0.0/**12**
  - 256 Class C blocks: **192.168.0**.X – **192.168.255**.X
    - I.e., **192.168**.0.0/**16**

Network Address Translation

Network Address Translation (NAT)

- Generic translation mechanism
  - Allows not just to spare public IP addresses
    - Probably the most successful mitigating solution
- Deployment
  - **Inner private and outer public networks**
  - Separated by a router implementing the NAT mechanism
- Disadvantages
  - **Decreases the overall throughput**
  - **May not always work**
    - Since the translation primarily works at L3 / L4 layers
    - Therefore it is incapable of modifying L7 data which may also contain the same addresses otherwise subjected to translation

NAT Principle

Delivery mechanism

- **Outgoing** transmission
  - (1) **inner node sends an IP datagram** in a standard way
    - Source address is set to private IP_S address of a given node
    - Destination address is IP_T address of the intended recipient
  - (2) this **datagram is captured by the router** and **NAT is applied**
    - Source address is replaced with appropriate public IP_P address
  - (3) **modified datagram is then sent to the public network**
    - As if its sender was actually the router itself
- **Incoming** transmission
  - (4) response from the target recipient is delivered back to IP_P
  - (5) this response is captured by our router and translated
    - Destination address is replaced with the original IP_S
  - (6) modified response is internally sent to our node

Static and Dynamic NAT

Static **NAT**

- Mapping table is **fixed and given in advance**
  - Each node will always be mapped to the same public address
    - And so individual bindings are predictable in advance
- Inner nodes are always **reachable from outside**
  - In terms of incoming transmissions initiated from outside
    - I.e., not in terms of responses to our outgoing transmissions
    - Since these are always deliverable
- Disadvantage
  - **Sizes of both public and private blocks must be identical**
    - And so there is no saving effect
  - At least unless certain inner nodes shall not communicate at all

Static and Dynamic NAT

Dynamic **NAT**

- Records in mapping tables are added / removed **dynamically**
  - I.e., individual **bindings are created on demand**
    - Only when they are really needed (new outgoing connection)
    - And will only exist for a limited period of time
  - **Assigned address may always be different** for a given node
    - And so it cannot be determined in advance
- Inner nodes are **not (automatically) reachable from outside**
  - **Unless their bindings already exist**
  - This may be treated as a disadvantage
    - As well as on the contrary…
    - Since NAT can therefore act as a kind of **firewall**
- **Not all inner nodes must necessarily have their bindings**
  - And so we can really save public addresses

Port Address Translation

Network Address and Port Translation (NAPT)

- Also abbreviated just as Port Address Translation (**PAT**)
- **Motivation**
  - Suitable when we do not have as many public addresses as nodes in our private network
    - This often means we may only have just a **single public address**
- **Principle**
  - All inner nodes are mapped to the same public address
  - Individual transmissions are **distinguished via different ports**

PAT Principle

Delivery mechanism

- **Outgoing** transmission
  - (1) **inner node sends an IP datagram** in a standard way
    - Source transport private address is IP_S:$port_S$
    - Destination transport address of recipient is IP_T:$port_T$
  - (2) this **datagram is captured by the router** and **PAT is applied**
    - Source address is replaced with appropriate public IP_P:$port_P$
    - Datagram TCP / UDP payload is also accordingly translated
  - (3) **modified datagram is then sent to the public network**
    - As if its sender was actually the router itself
- **Incoming** transmission
  - Steps (4), (5), and (6) for response delivery are analogous…

PAT Observations

Dynamic character

- Created **bindings** always exist only for a **limited period of time**
  - And so responses can only be delivered during this window
- Depends on a **particular** L4 **protocol** and its **implementation**
  - **UDP**: 30 – 300 seconds
  - **TCP**: 30 – 60 minutes

PAT alternatives

- How the assigned public IP_P:$port_P$ address is to be resolved?
  - It can depend solely on the source private IP_S:$port_S$ address
    - **Full** / **IP Restricted** / **Port Restricted Cone NAT**
  - As well as even on the intended destination IP_T:$port_T$ address
    - **Symmetric NAT**
- Incoming transmissions from which nodes will be accepted?

PAT Alternatives

Full Cone NAT

- Assigned public IP_P:$port_P$ depends…
  - Solely on private IP_S:$port_S$ address
    - I.e., assigned public address remains the same even for further connections to possibly different intended destinations
- **Responses** to IP_P:$port_P$ are accepted from…
  - **All IP addresses and all their ports** without any limitation

IP Restricted Cone NAT (or just **Restricted Cone NAT**)

- Assignment rules are the same
- **Responses** to IP_P:$port_P$ are accepted only from…
  - **Contacted IP addresses and still all their ports**

PAT Alternatives

Port Restricted Cone NAT

- Assignment rules are the same once again
- **Responses** to IP_P:$port_P$ are accepted only from…
  - **Contacted IP addresses and only from contacted ports**

Symmetric NAT

- Assigned public IP_P:$port_P$ depends…
  - Both on private IP_S:$port_S$ and destination IP_T:$port_T$ addresses
    - I.e., assigned public address (in particular its port) changes every time a different destination is requested
- **Responses** to IP_P:$port_P$ are accepted only from a given single…
  - **Contacted IP address and its only contacted port**

IPv6 Addresses

Motivation

- IPv4 exhaustion problem
  - **Temporary mitigating measures** worked
    - And actually worked better than it was perhaps anticipated
    - Since the first exhaustion threat appeared around 1990
    - And IPv4 is still the primary approach even after 30 years
  - Nevertheless, **permanent solution was needed**
    - Formerly intended **Class E** was not found realistically applicable
    - Since IPv4 would need to be entirely redesigned
    - Together with dozens of other related protocols (OSPF, RIP, …)
  - And so an entirely new solution was introduced
- **IPv6 protocol and addresses**
  - Primarily **larger address space**
  - But also several other **major improvements** and changes

IPv6 Addresses

IPv6 addresses

- Differences to IPv4
  - **More address hierarchy levels**
    - Allows for better aggregation
    - And so smaller and localized routing tables
  - **Easier assignment of addresses**
    - Including autoconfiguration options
    - Network interface can have several unicast addresses at a time
  - **Introduction of anycast addresses**
    - And removal of broadcast addresses
  - **Significantly larger address space**
    - 128 bits (16 bytes) instead of just 32 bits (4 bytes)
    - Theoretically $\approx 3.4 \times 10^{38}$ individual addresses
    - Compared to just $\approx 4.3 \times 10^{9}$ in case of IPv4

IPv6 Addresses

IPv6 addresses

- **Notation**
  - Eight 2-byte-long words, written as 4-digit hexadecimal numbers, mutually separated by colons
  - E.g.: 805b:2d9d:dc28:0000:0000:fc57:d4c8:1fff
- **Abbreviations**
  - **Suppressed leading zeros**
    - Leading zeros in individual words are truncated
    - E.g.: 805b:2d9d:dc28:**0**:**0**:fc57:d4c8:1fff
  - **Zero-compressed**
    - One adjacent group of zero words is entirely omitted
    - E.g.: 805b:2d9d:dc28::fc57:d4c8:1fff
  - **Mixed notation** for **embedded IPv4 addresses**
    - E.g.: 0:0:0:0:0:0:**212.200.31.255** or **::212.200.31.255**

IPv6 Addresses

Types of addresses

- **Unicast addresses**
  - Allow for standard communication with **individual nodes**
- **Multicast addresses**
  - Allow for communication with **all nodes in a given group**
    - Always start with ff/8 (11111111_B…)
  - Can be used to simulate traditional **broadcasts**, too
- **Anycast addresses**
  - Allow for communication with **one node from a given group**

IPv6 Addresses

Types of **unicast** addresses

- **Global Unicast**
  - Globally unique public individual addresses
- **Local Unicast** (**Unique Local Addresses**) (**ULA**)
  - Private addresses unique within all subnets of a given site
    - Labeled with such site and subnet identifiers
    - Therefore suppressed chances of accidental leak outs
  - Always start with fc00/7 (1111110_B…)
- **Link Local**
  - Private addresses unique within a given individual subnet
    - Allow for **autoconfiguration** based on MAC addresses
  - Always start with fe80/10 (1111111010_B…)
- **Site Local**
  - Private addresses unique within all subnets of a given site
    - Should no longer be used

IPv6 Addresses

Global individual addresses

- Three components
  - Site **identifier**
    - Identifies a particular site = group of related networks
  - Subnet **identifier**
    - Identifies a particular network within a given site
  - Interface **identifier**
    - Identifies a particular node within a given subnet
- **Routing** mechanisms
  - Public **topology**
    - Routing algorithms in public Internet only work with sites
  - Site **topology**
    - Internal site topology is concealed to the public Internet

Addressing at L4

Port **numbers**

- Assigned to **access points** between L4 and L7 in order to allow **end-to-end** communication of individual **application entities**
  - Within a given end node
  - **Separately for each transport protocol** (**TCP**, SCTP, DCCP, **UDP**)
    - Yet in practice usually the same for all these protocols
- Necessary for both **incoming and outgoing** directions
- Allow for the identification of **transport connections**
  - Tuple (sender IP_1:port_1, protocol, recipient IP_2:port_2)
    - **Target** of the **outgoing** transmission (IP_2:port_2, protocol)
    - **Source** of the **incoming** transmission (IP_1:port_1, protocol)
- **Requirements**
  - Ports must be **unique, abstract, implicit and static**

Ports

Port numbers

- **16-bit** long integer numbers: permitted **values 0 – 65535**
- System and registered ports maintained by **IANA**
  - **Internet Assigned Numbers Authority**
- Online table of **port numbers** and **service names**
  - https://www.iana.org/assignments/service-names-port-numbers/

Types of ports

- **System Ports** (**Well Known Ports**) (0 – 1023)
  - **Assigned to one purpose** (usually system-oriented services)
  - Should not be used for any other purpose
  - Examples
    - FTP (21), SSH (22), SMTP (25), DNS (53), HTTP (80), POP3 (110), NTP (123), IMAP (143), HTTPS (443), …

Ports

Types of ports (cont'd)

- **User Ports** (**Registered Ports**) (1024 – 49151)
  - **Assigned to one purpose** again
  - But may freely be used for any other purpose
  - Examples
    - Registered: MySQL (3306), PostgreSQL (5432), Redis (6379), Neo4j (7474), MongoDB (27017), …
    - Not registered: Riak (unasigned 8087 and 8098), Cassandra (assigned 7000), …
- **Dynamic Ports** (**Private Ports**) (49152 – 65535)
  - Not assigned, available for unrestricted usage
  - Usually for **outgoing transmissions**

Addressing at L7

Requirements and expectations

- **Various kinds of objects** need to be identified at L7
  - Web pages, files, e-mail addresses, publications, …
- Two aspects actually need to be covered
  - **Identification**
    - So that objects of one kind can mutually be distinguished
    - At least **locally** (within a given end node) but also **globally**
  - **Location**
    - In terms of a particular node where such objects can be found
  - It make sense to logically decouple both these aspects
- **Each application** may have its own proprietary **naming system**
  - Yet it makes sense to pursue **unification** and **coordination**
  - As well as to recycle approaches that already exist

URI Framework

Uniform Resource Identifier (URI)

- Generic, federated and extensible **naming system**
  - Allows to identify basically anything
    - Including real-world objects (people, places, concepts, …)
- Types of identifiers
  - **Uniform Resource Locator (URL)**
    - **Web resource reference** (web address)
    - Specifies particular location as well as retrieval mechanism
  - **Uniform Resource Name (URN)**
    - **Globally unique persistent resource identifier**
    - Does not imply any location, not widely used
  - **Uniform Resource Characteristics (URC)**
    - Description of **meta data** about URLs or URNs (citations, …)
    - Never standardized, not even implemented

URI Examples

Sample **URLs**

- `http` scheme (**Hypertext Transfer Protocol**)
  - Addresses of web pages or other resources
  - E.g.: **http**://www.mff.cuni.cz/en/index.php?page=people#5460
- `ftp` scheme (**File Transfer Protocol**)
  - Paths to files or directories accessible using the FTP protocol
  - E.g.: **ftp**://svoboda:password@ulita.ms.mff.cuni.cz/
- `file` scheme
  - Host-specific paths on local or remote **file systems**
  - E.g.: **file**:///home/svoboda/NSWI090/Lecture-03-Layers.pdf
- `mailto` scheme
  - **E-mail addresses** including additional parameters
  - E.g.: **mailto**:svoboda@ksi.mff.cuni.cz?subject=NSWI090

URI Examples

Sample **URLs**

- `tel` scheme
  - **Telephone numbers**
  - E.g.: **tel**:+420-951-554-250
- `sip` scheme (**Session Initiation Protocol**)
  - Participants of multimedia sessions such as **voice calls** (VoIP, …)
  - E.g.: **sip**:martin.svoboda@mff.cuni.cz
- `jdbc` scheme (**Java Database Connectivity**)
  - Connections to **relational databases** from Java applications
  - E.g.: **jdbc**:postgresql://nosql.ms.mff.cuni.cz:5432/database

URI Examples

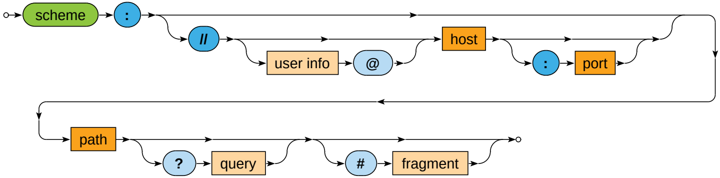
Sample **URNs**

- `isbn` namespace (**International Standard Book Number**)
  - Printed or electronic **books**
  - E.g.: urn:**isbn**:9780132126958
- `issn` namespace (**International Standard Serial Number**)
  - Printed or electronic **serial publications** (journals, …)
  - E.g.: urn:**issn**:0302-9743
- `ietf` namespace (**Internet Engineering Task Force**)
  - IETF family of RFC, STD, FYI, and BCP documents
  - E.g.: urn:**ietf**:rfc:2648
- `iso` (**International Organization for Standardization**)
  - **Standards** and other technical specifications
  - E.g.: urn:**iso**:std:iso-iec:9075:-1:ed-5:en

URI Structure

Generic syntax

- May further be restricted by particular schemes
- **Syntax diagram** (for context-free grammars)



  - **Green** boxes: **literals**
    - Expected to be replaced with a particular value
  - **Blue** boxes: **constants** (preserved as they are)
  - **Orange** boxes: **non-terminals**
    - Unfolded to more complicated fragments

URI Schemes

URI components

- **Scheme**: case-insensitive **scheme name** (usually lower-case)
- **Authority**
  - **User info**: authentication tokens such as **name** and **password**
    - Deprecated for security reasons
  - **Host**: **domain name**, **IP address**, or a different registered name
  - **Port**: transport layer **port**
- **Path**: usually **hierarchical path** with individual segments
- **Query**: usually parameters in a form of **attribute / value pairs**
- **Fragment**
  - Reference to a **secondary resource** related to the primary one
    - E.g.: anchors in HTML pages, classes in OWL ontologies, …

URI Framework

Both **schemes** and **namespaces** are registered with **IANA**

- **URI schemes**
  - https://www.iana.org/assignments/uri-schemes/
  - Current status (April 2021)
    - $\approx$ 100 permanent, 230 provisional, and 10 historical schemes
- **URN namespaces**
  - https://www.iana.org/assignments/urn-namespaces/
  - Current status (April 2021)
    - $\approx$ 70 namespaces

Internationalized Resource Identifier (IRI)

- Just an extended version of the traditional URIs
- Allows to use most of **Unicode characters**
  - And so Chinese, Japanese, Korean or other national characters

Lecture Conclusion

L2: **MAC** addresses

- **EUI-48** and EUI-64 numbering systems, **OUI**, M and X bits

L3: **IPv4** addresses

- **Network and relative** parts
- **Classes** A, B, C, D, and E
- Special and **multicast** addresses
- **Subnetting** and **supernetting**
- **CIDR** blocks and prefixes
- RIR, NIR, and LIR **registries**
- **Private addresses** and **NAT / PAT** translation

Lecture Conclusion

L3: **IPv6** addresses

- **Site, subnetwork, and interface** parts
- Types of addresses

L4: **port** numbers

- System / User / Dynamic ports

L7: **URI** identifiers

- URI (IRI) framework: **URL** locators, **URN** names