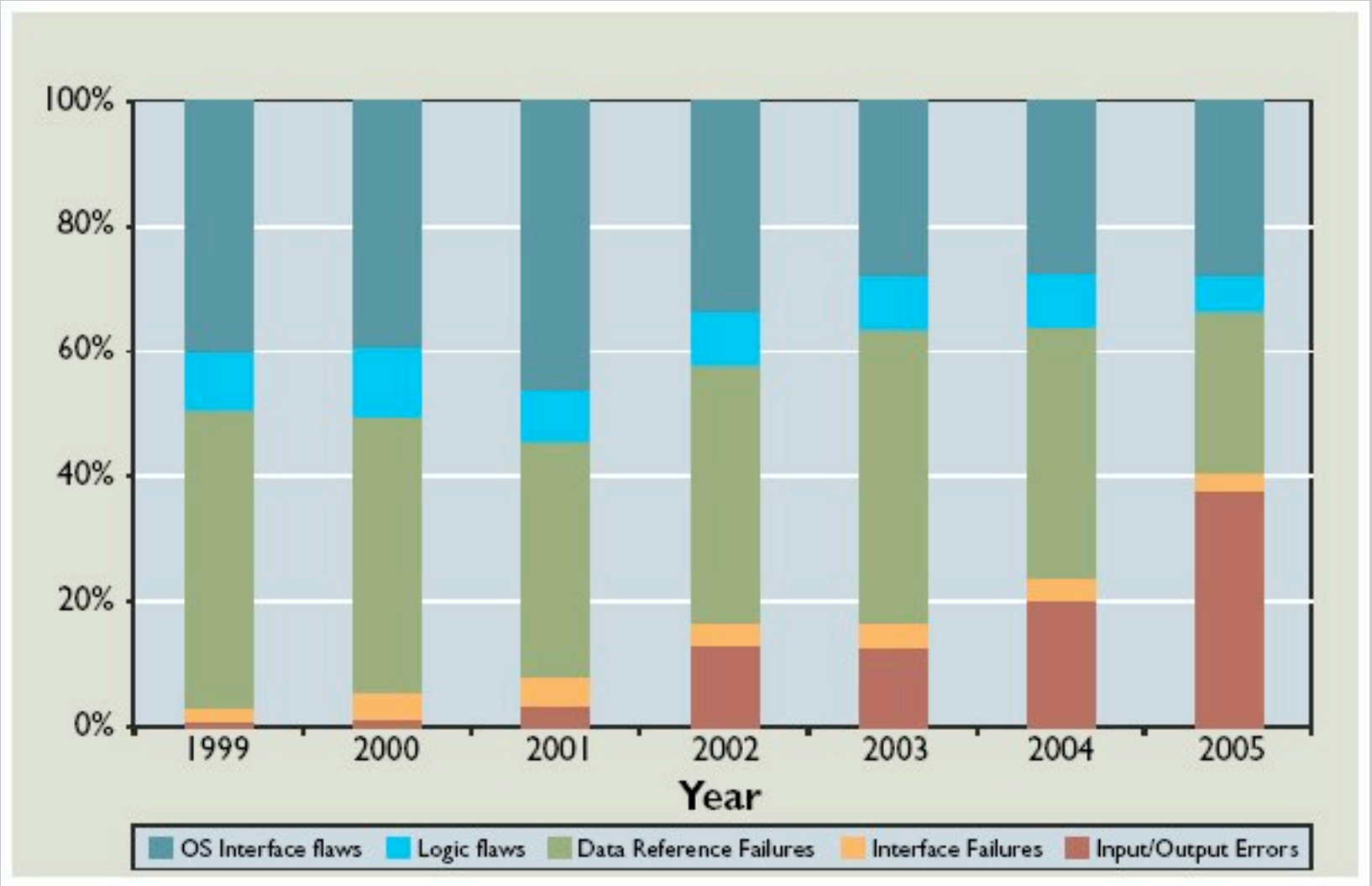
Design and Implementation of an object-oriented, secure TCP/IP Stack

Hannes Mehnert, Andreas Bogk
23c3
27. December 2006

Overview

- Common software vulnerabilities
- Dylan
- Architecture of IP-Stack

CVE sorted by bug class



"Software Security is Software Reliability", Felix Lindner, CACM 49/6

Data Reference Failures – Workarounds and solutions

- Buffer overflows:
  - Workarounds:
    - Stack canaries
    - Write xor execute
    - Randomized address spaces
  - Solution: Bounds checking
- Integer overflows:
  - Solution: bignums, exception on overflow
- Premature memory release
  - Solution: Automatic memory management

Input/Output Errors

- SQL injections
- Cross-site scripting
- Blue boxing
- 0-byte poisoning
- Perl OPEN

Interface Failures

- Format String Exploits
  - problem: varargs are not type safe
  - solution: language with type safe varargs
- Race conditions

OS Interface Flaws

- Directory Traversal
- Illegal File Access
- Remote Code Execution

Conclusion

- Prevention strategies exist for most bug classes
- Data Reference Failures can be avoided by choice of suitable programming language

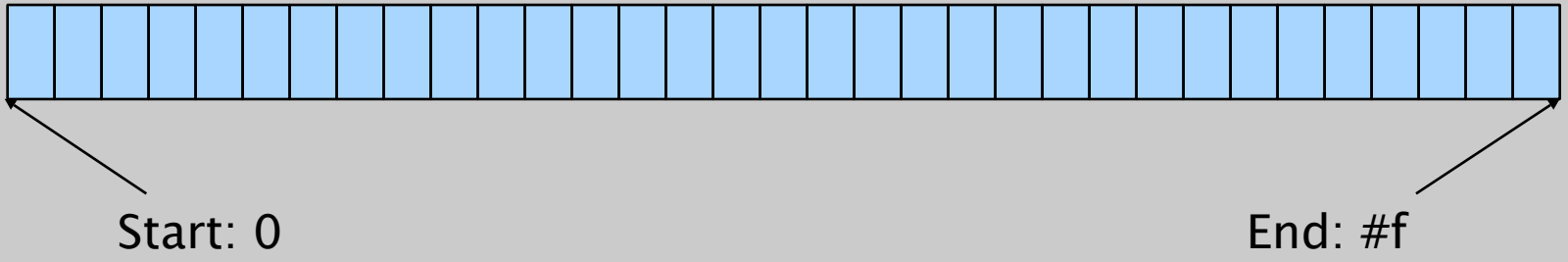
Dylan

- Object oriented
- Functional aspects (higher order functions)
- Automatic memory management
- Dynamic and strong typing
- Bounds checks
- Optional type inference
- Supports encapsulation
- Features like scripting language (rapid prototyping), but compiled (performance)

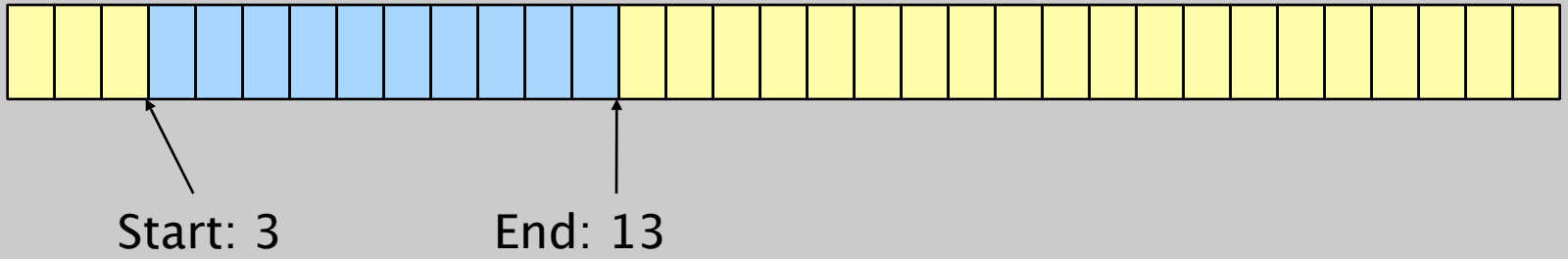
Architecture for secure networking

- Packetizer – to parse and assemble protocols
  - Inspired by scapy
- Flow-Graph library – to specify flow of packets
  - Inspired by click
- Layering-mechanism – to stack protocols
  - Inspired by conduit+

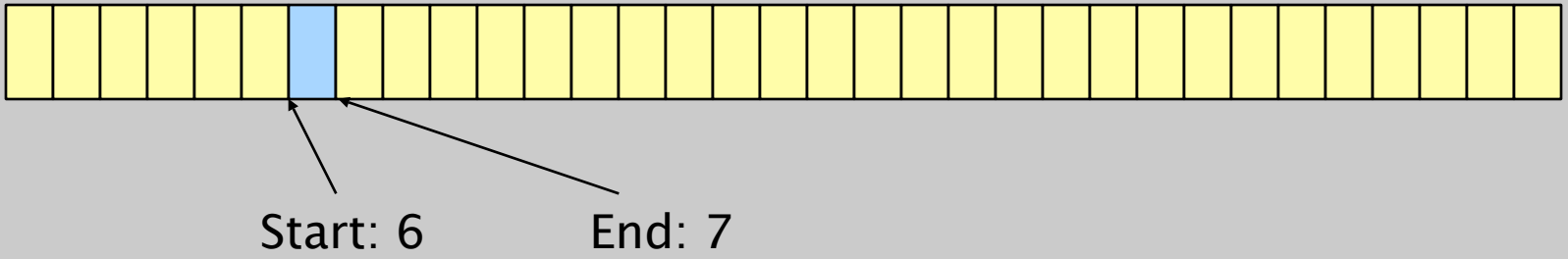
<stretchy-byte-vector-subsequence>



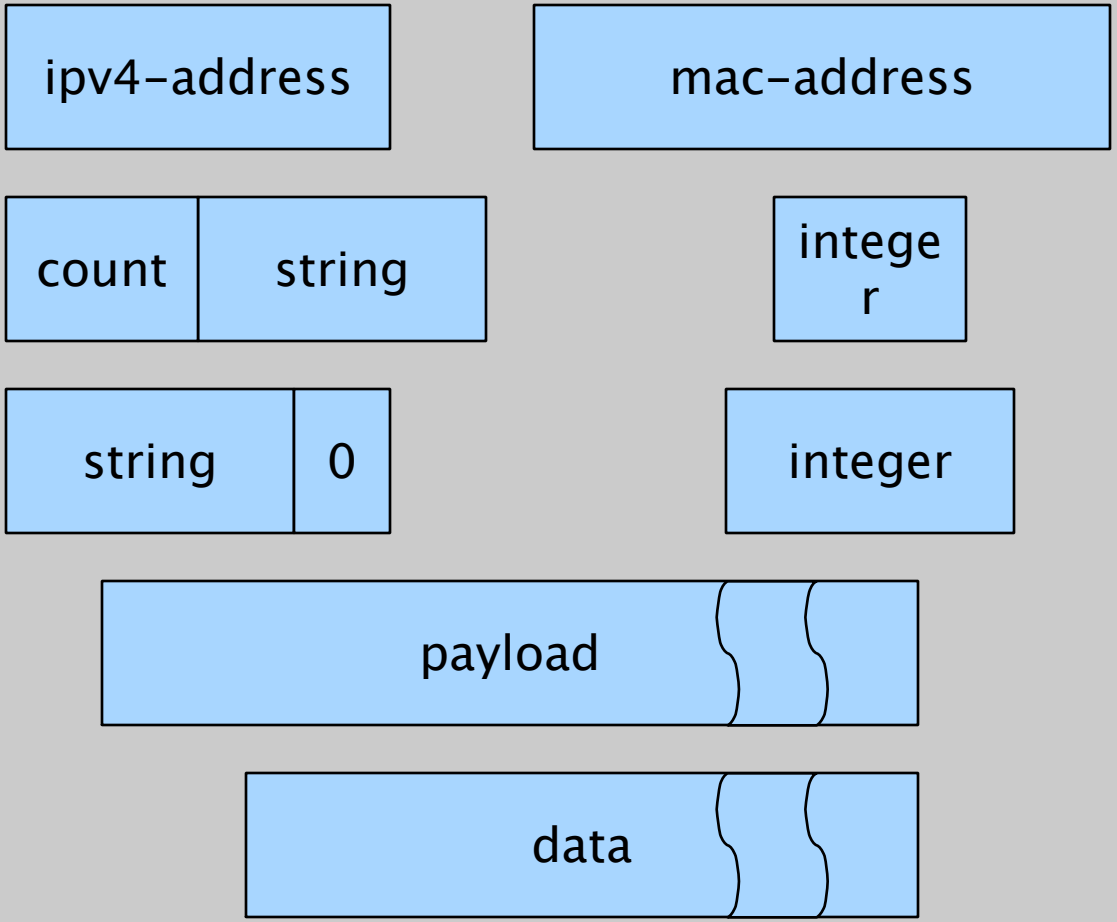
let subseq = subsequence(bytes, start: 3 * 8, length: 8 * 10)



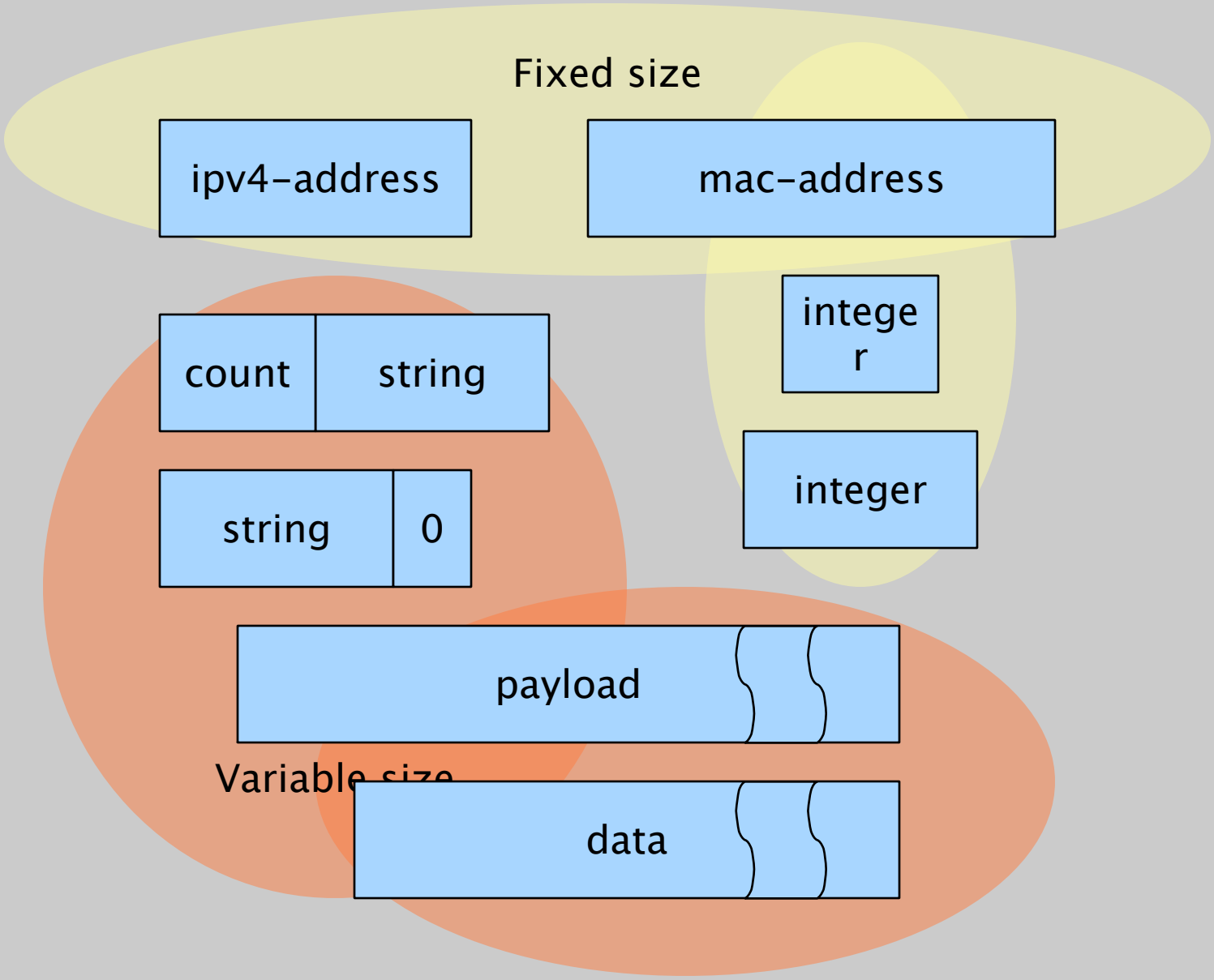
subsequence(subseq, start: 3 * 8, length: 8)



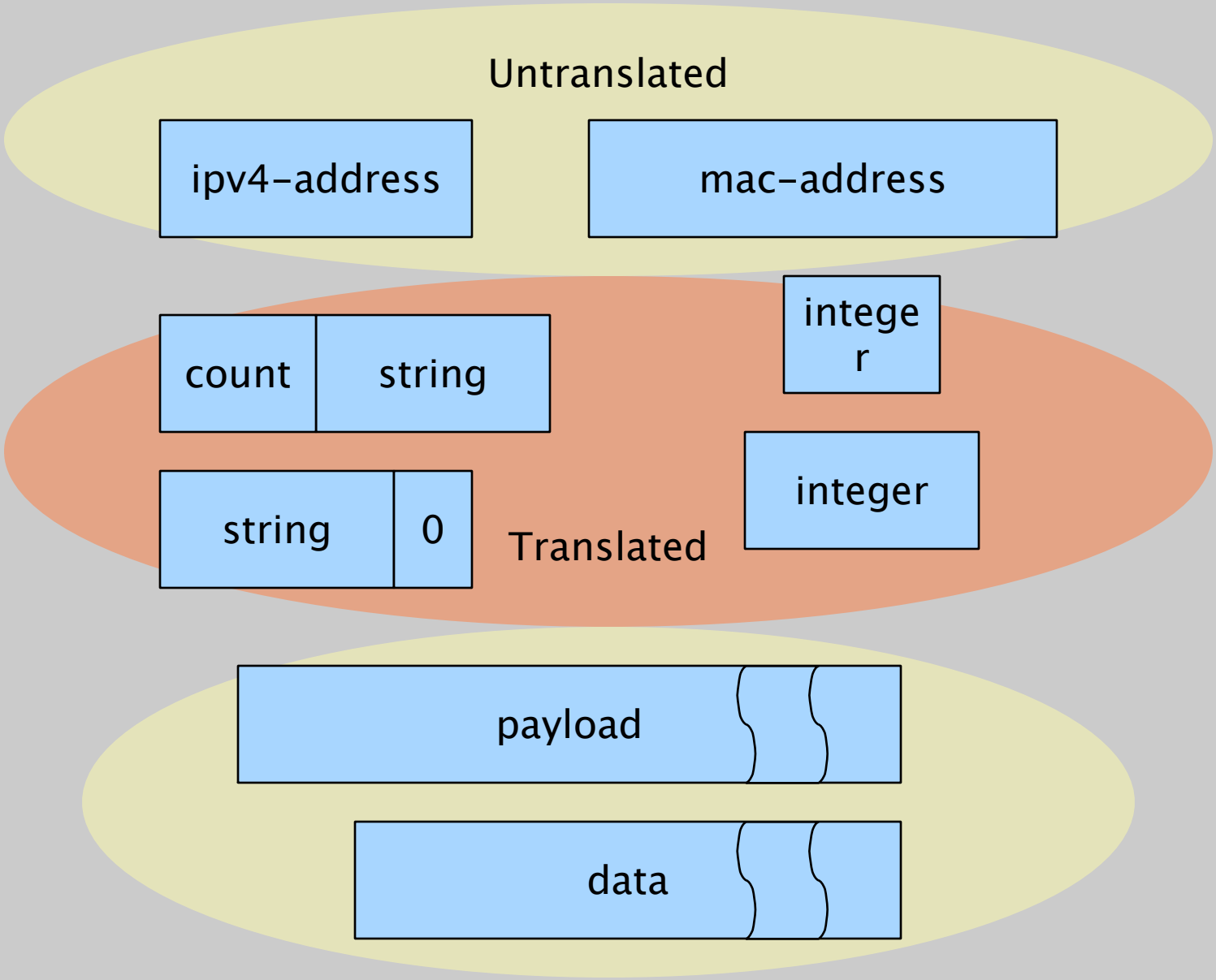
Frames


ipv4-address
mac-address
count
string
intege
r
string
0
integer
payload
data

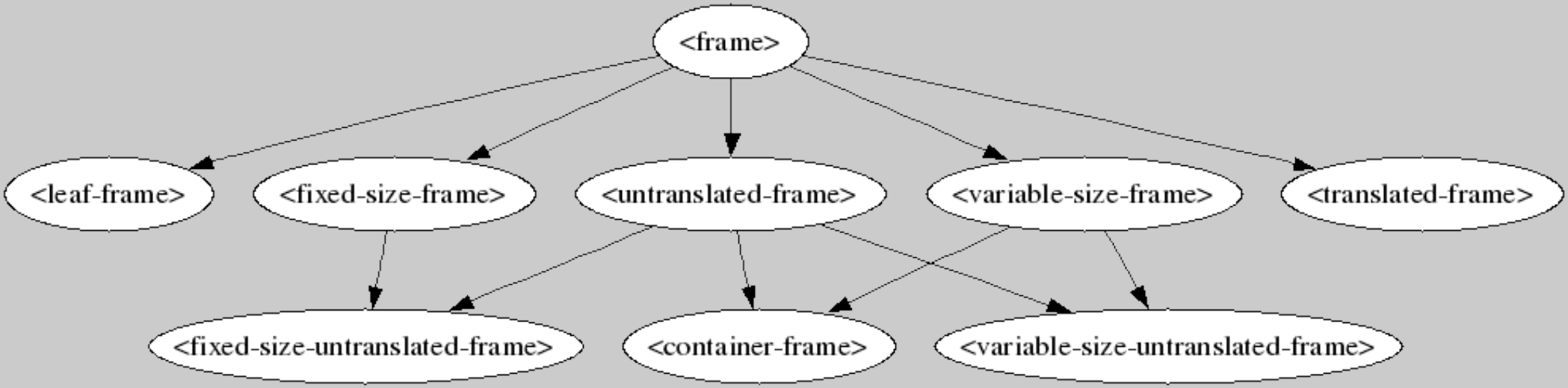
Frames – Size property



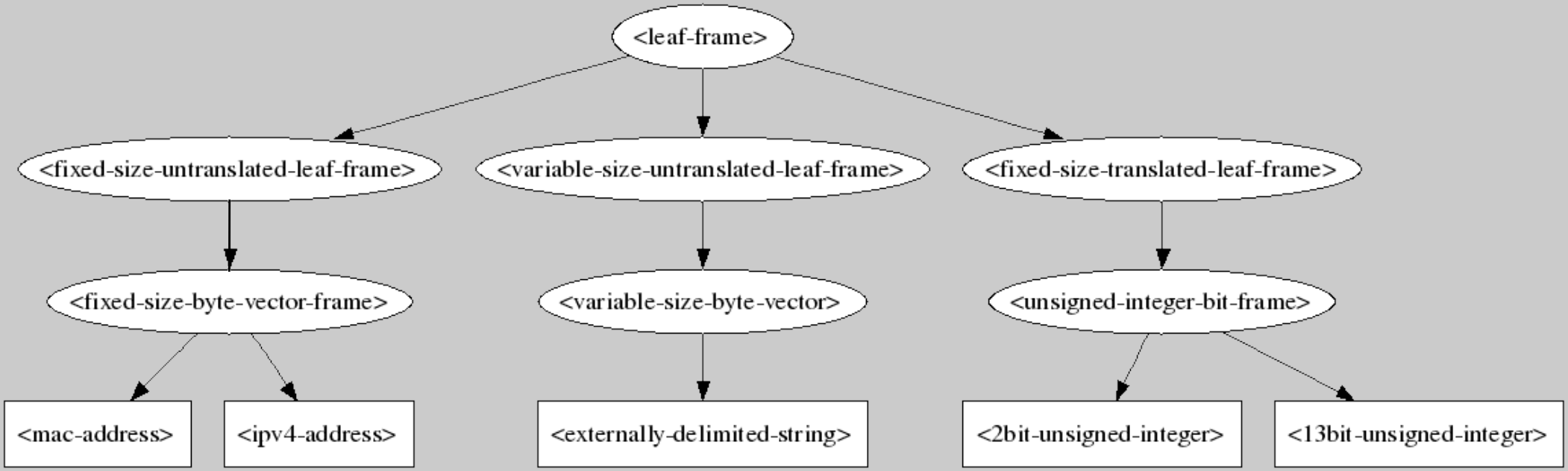
Frames – Translation property



<frame>

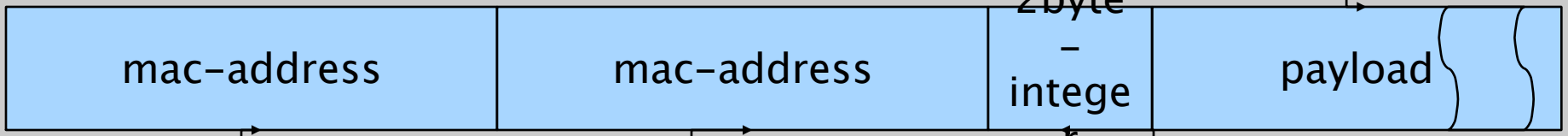

<frame>
<leaf-frame>
<fixed-size-frame>
<untranslated-frame>
<variable-size-frame>
<translated-frame>
<fixed-size-untranslated-frame>
<container-frame>
<variable-size-untranslated-frame>

<leaf-frame>


<leaf-frame>
<fixed-size-untranslated-leaf-frame>
<variable-size-untranslated-leaf-frame>
<fixed-size-translated-leaf-frame>
<fixed-size-byte-vector-frame>
<variable-size-byte-vector>
<unsigned-integer-bit-frame>
<mac-address>
<ipv4-address>
<externally-delimited-string>
<2bit-unsigned-integer>
<13bit-unsigned-integer>

Container Frames

Name: payload
type: select (type-code)
#x800 => <ipv4-fram
#x806 => <arp-frame
end,
static-start: 14 * 8;

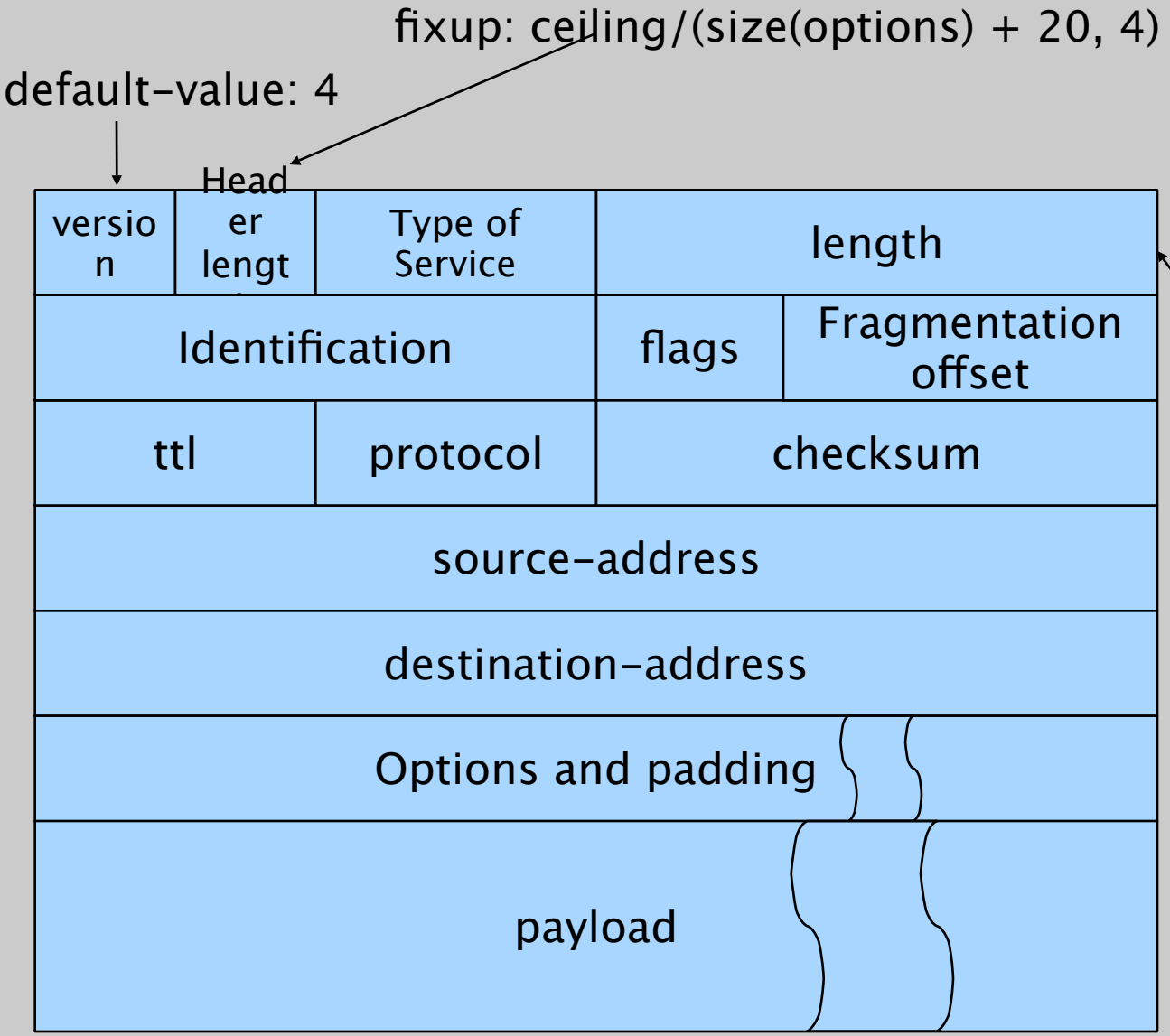


Name :destination-address
type: mac-address
static-start: 0
static-length: 6 * 8

Name: source-address
type: mac-address
static-start: 6 * 8
static-length: 6 * 8

Name: type-code
type: 2byte-big-endian-unsigned-integer
static-start: 12 * 8
static-length: 2 * 8

IPv4



fixup: frame.header-length +si
(frame.payload)

type-function: select (frame.protocol)
6 => <tcp-frame>
17 => <udp-frame>
end,
start: frame.header-length * 4 * 8,
end: frame.length * 8;

Frame inheritance, repeated fields

ip-option-header

flag	class	number

ip-options

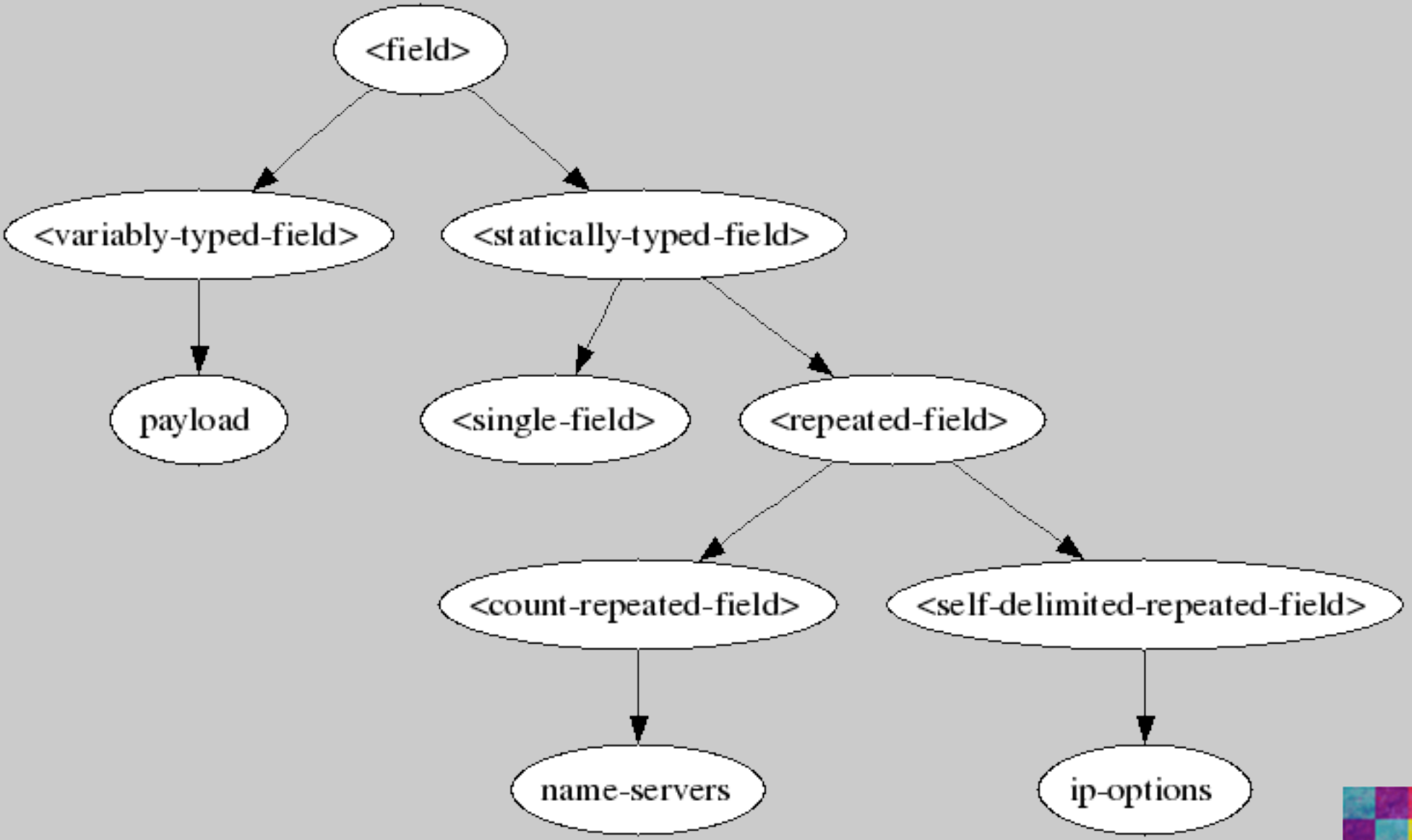
router-alert (20)	length	value

end-of-ip-options (0)

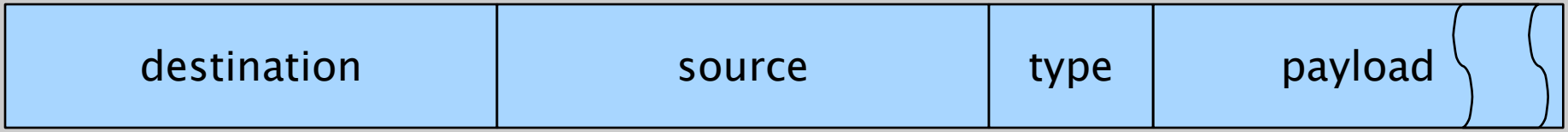
Options field in ipv4-frame

router-alert	timestamp	End-of-options	padding

<field>

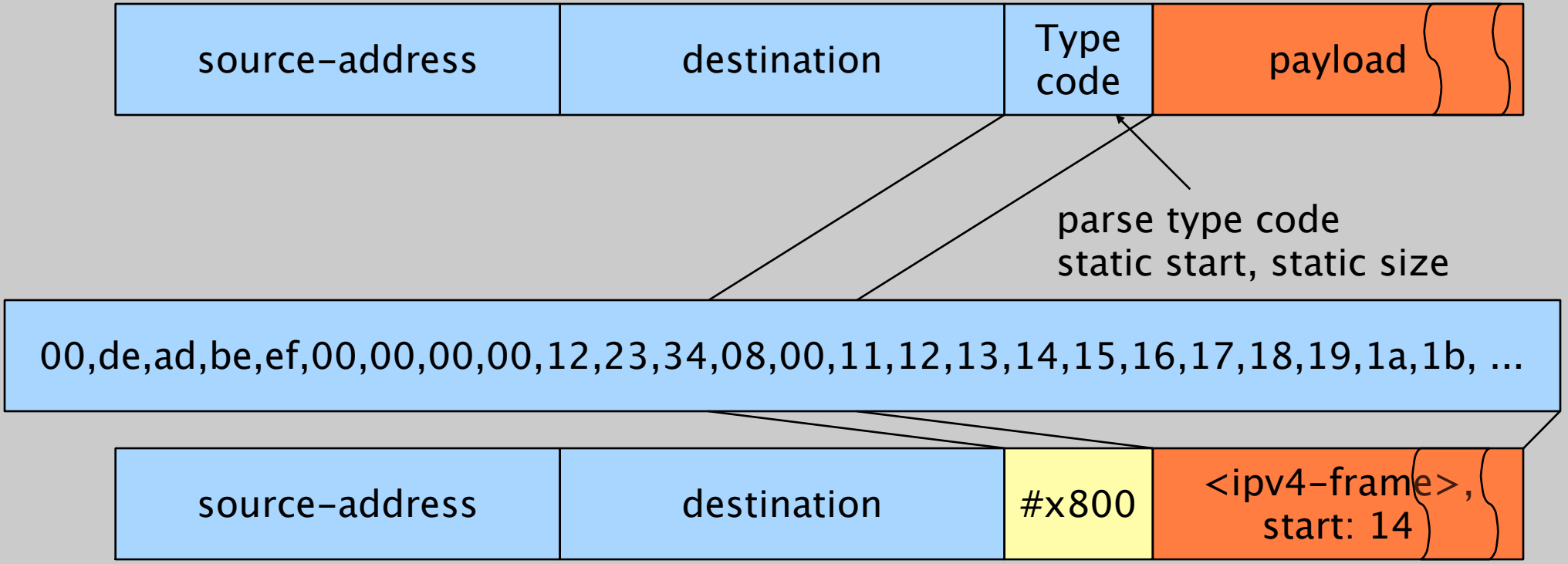

<field>
<variably-typed-field>
<statically-typed-field>
payload
<single-field>
<repeated-field>
<count-repeated-field>
<self-delimited-repeated-field>
name-servers
ip-options

Packetizer Code example

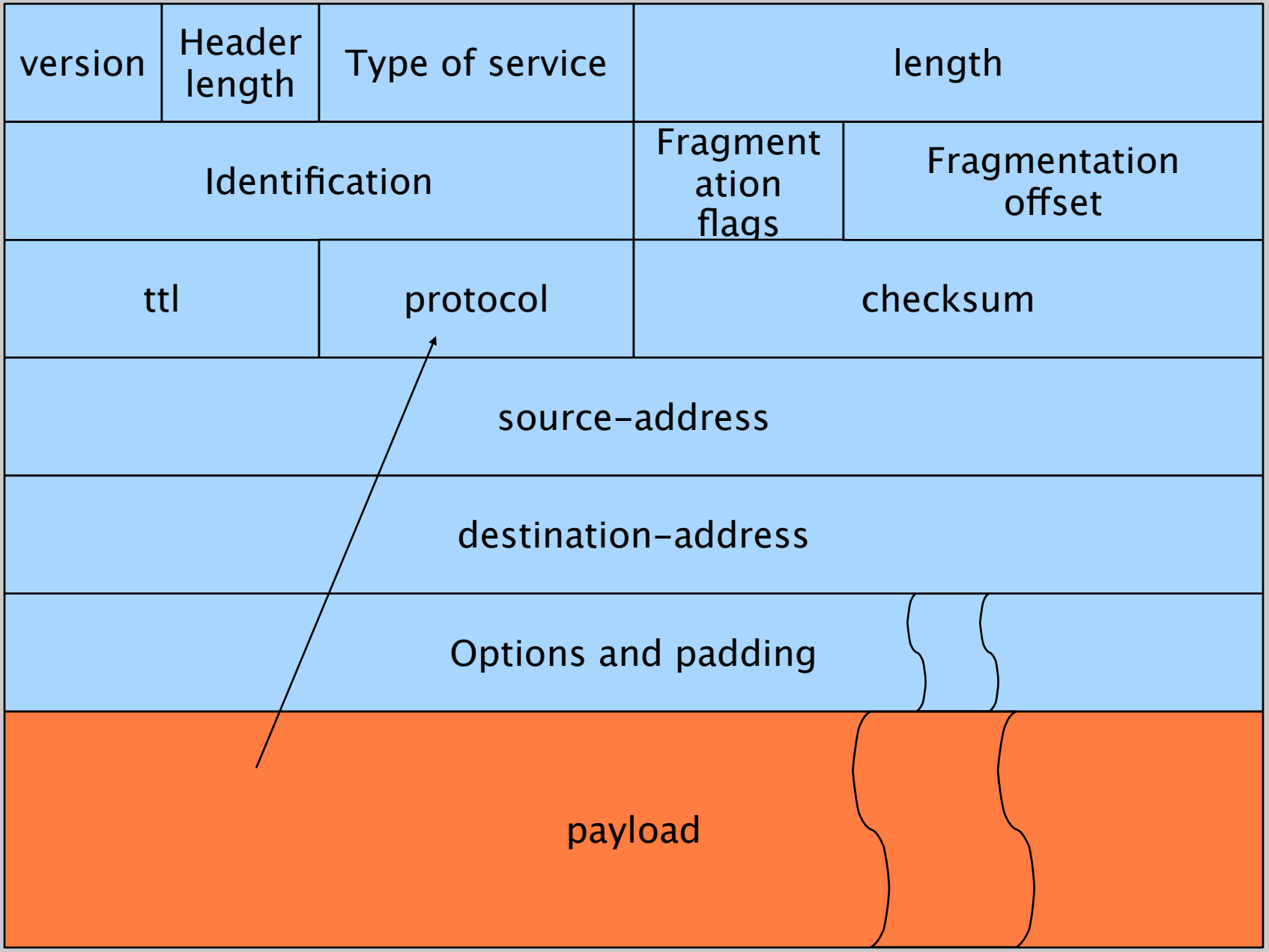



```
define protocol ethernet-frame (header-frame)
  field destination-address :: <mac-address>;
  field source-address :: <mac-address>;
  field type-code
    :: <2byte-big-endian-unsigned-integer>;
  variably-typed-field payload,
    type-function: select (frame.type-code)
                     #x800 => <ipv4-frame>;
                     #x806 => <arp-frame>;
                     otherwise <raw-frame>;
                   end;
end;
```

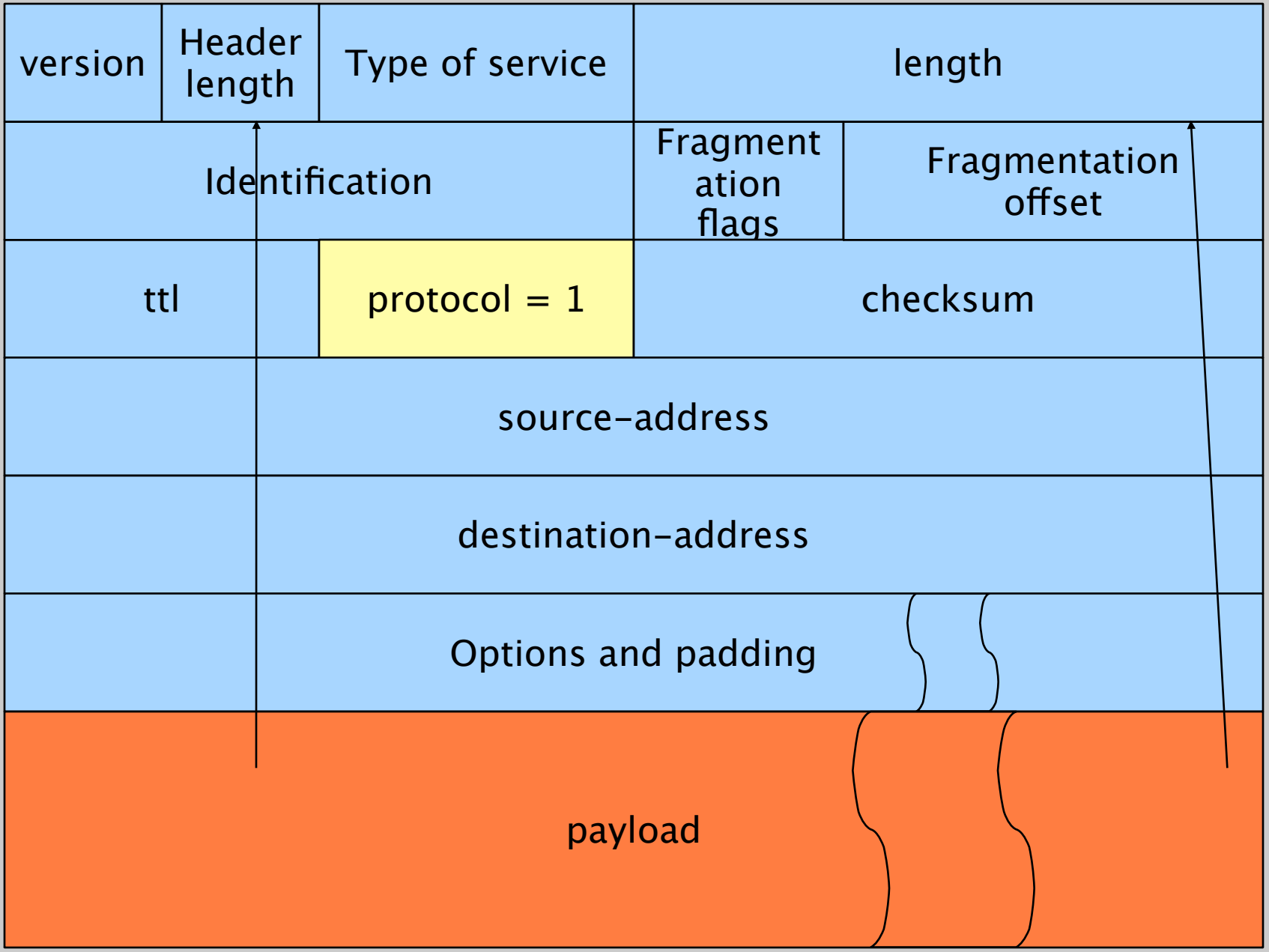
Parsing ethernet-payload



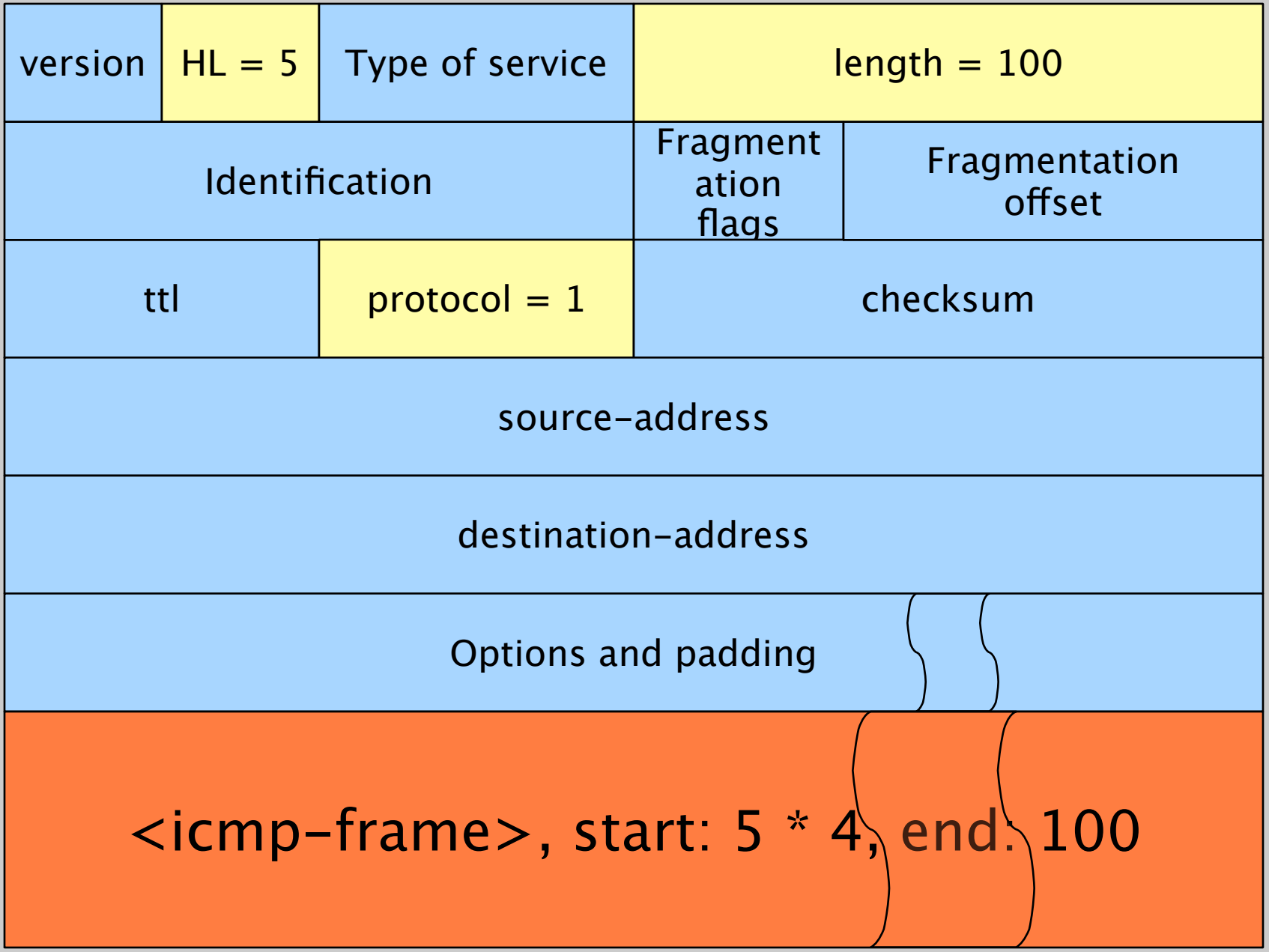
Parsing IPv4 payload – type



Parsing IPv4 payload – boundaries



Parsing payload of IPv4

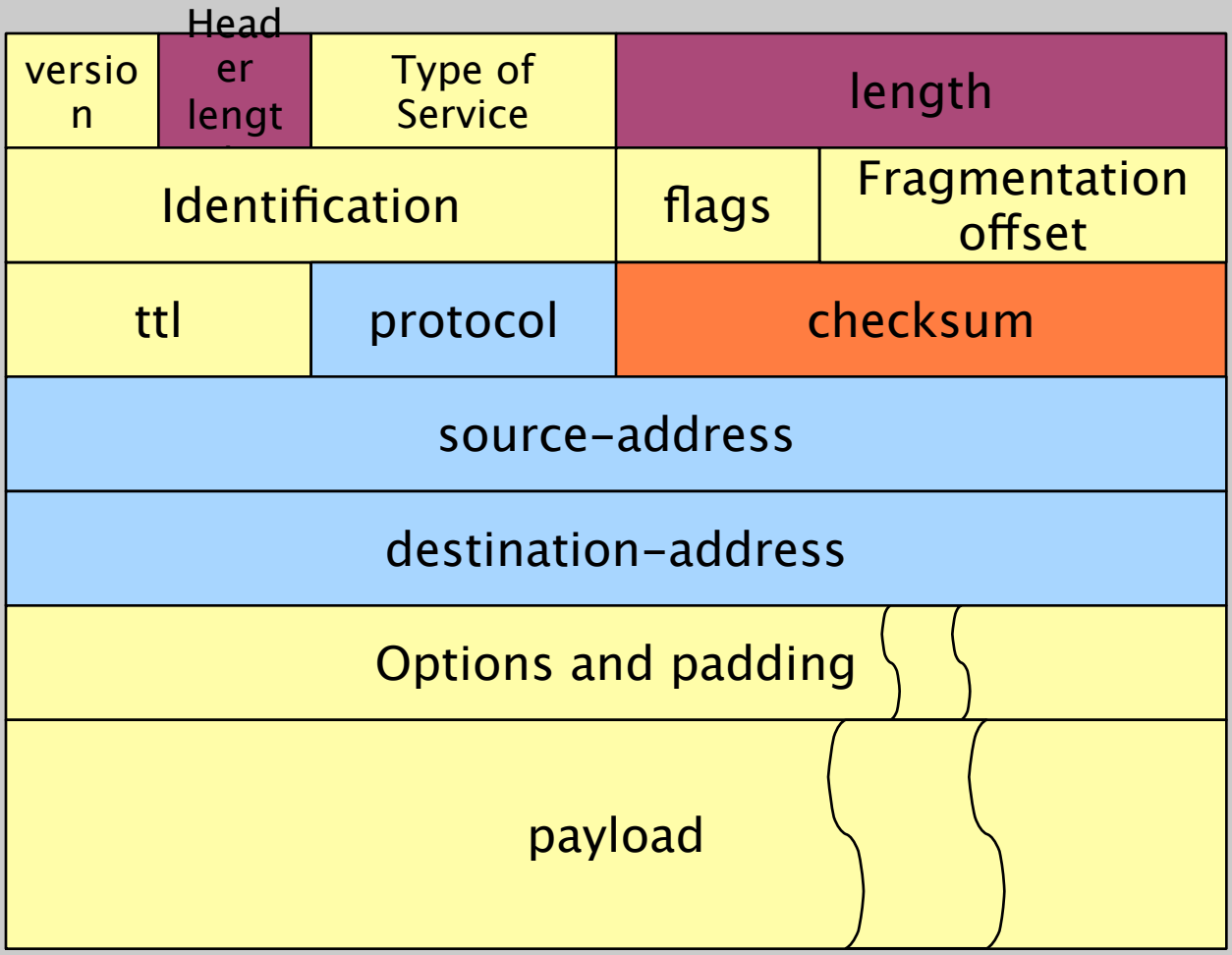


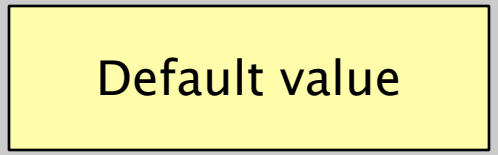
```
define protocol ipv4-frame (header-frame)
  field version :: <4bit-unsigned-integer> = 4;
  field header-length :: <4bit-unsigned-integer>,
    fixup: ceiling/(reduce(\+, 20, map(frame-size, frame.options)), 4);
  field type-of-service :: <unsigned-byte> = 0;
  field total-length :: <2byte-big-endian-unsigned-integer>,
    fixup: frame.header-length * 4 + frame-size(frame.payload);
  field identification :: <2byte-big-endian-unsigned-integer> = 23;
  field evil :: <1bit-unsigned-integer> = 0;
  field dont-fragment :: <1bit-unsigned-integer> = 0;
  field more-fragments :: <1bit-unsigned-integer> = 0;
  field fragment-offset :: <13bit-unsigned-integer> = 0;
  field time-to-live :: <unsigned-byte> = 64;
  field protocol :: <unsigned-byte>;
  field header-checksum :: <2byte-big-endian-unsigned-integer> = 0;
  field source-address :: <ipv4-address>;
  field destination-address :: <ipv4-address>;
  repeated field options :: <ip-option-frame> = make(<stretchy-vector>),
    reached-end?: method(value :: <ip-option-frame>)
                    instance?(value, <end-of-option-ip-option>)
                  end;
  variably-typed-field payload,
    start: frame.header-length * 4 * 8,
    end: frame.total-length * 8,
    type-function: payload-type(frame);
end;
```

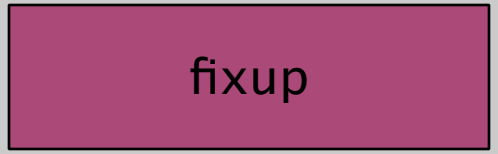
Parse code example

```
let frame = parse-frame(<ipv4-frame>,
                        packet: some-data);
format-out("Source address %=\n",
           frame.source-address);
```

Assembly IPv4







Assembly code example

```
let v4-frame = make(<ipv4-frame>,
  source-address: ipv4-address("23.23.23.23"),
  destination-address: ipv4-address("42.42.42.42"),
  protocol: 23);
let byte-vector = assemble-frame(v4-frame).packet;
```

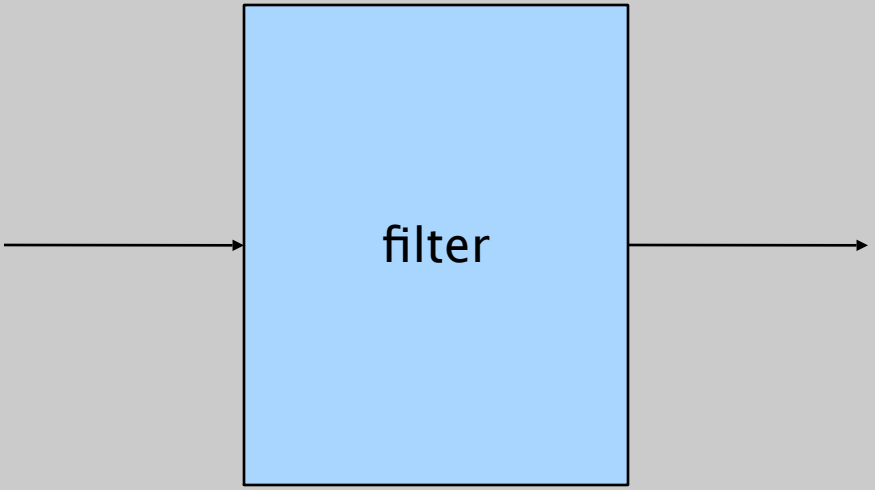
Assembly IPv4 - fixup

```
define method fixup! (frame :: <ipv4-frame>)
  frame.header-checksum
     := calculate-checksum(frame.packet);
  fixup!(frame.payload);
end;
```

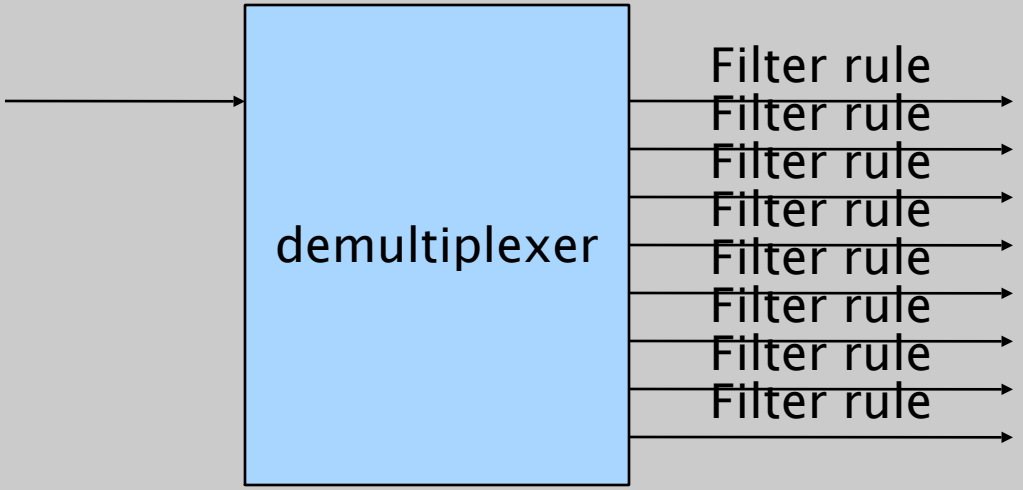
Filter language

- Operators
  - And &
  - Or |
  - Not ~
- Rules
  - Presence of a frame-type (“ipv4”, “~ (dns)”)
  - Value of a field (“ipv4.destination-address = 23.23.23.23”)
- “(udp.source-port = 53) | (udp.destination-port = 53)”

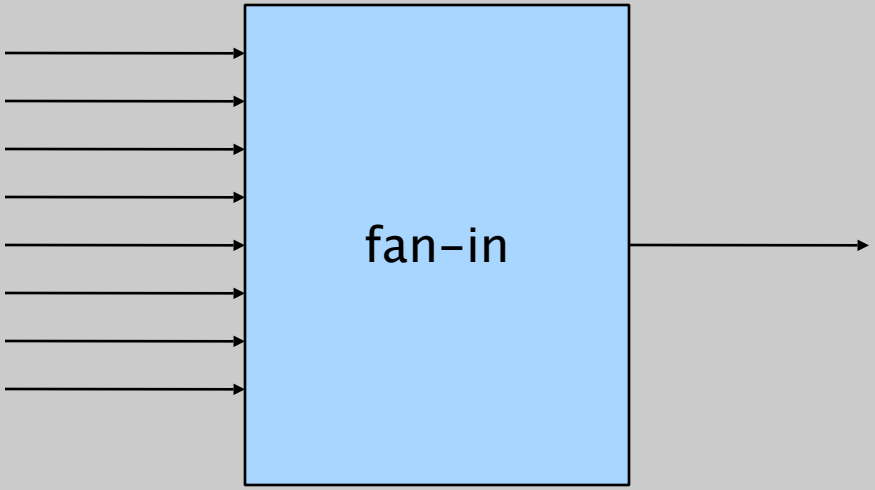
Flow-Graph



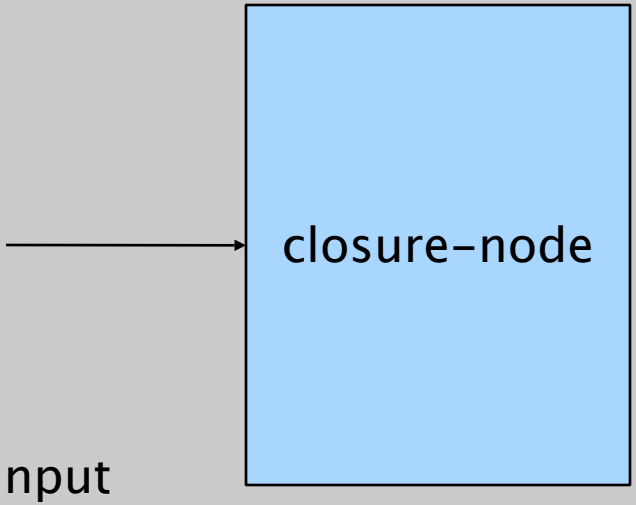
One input
one output



One input
multiple outputs,
each is associated with a filter rule



Multiple inputs
one output



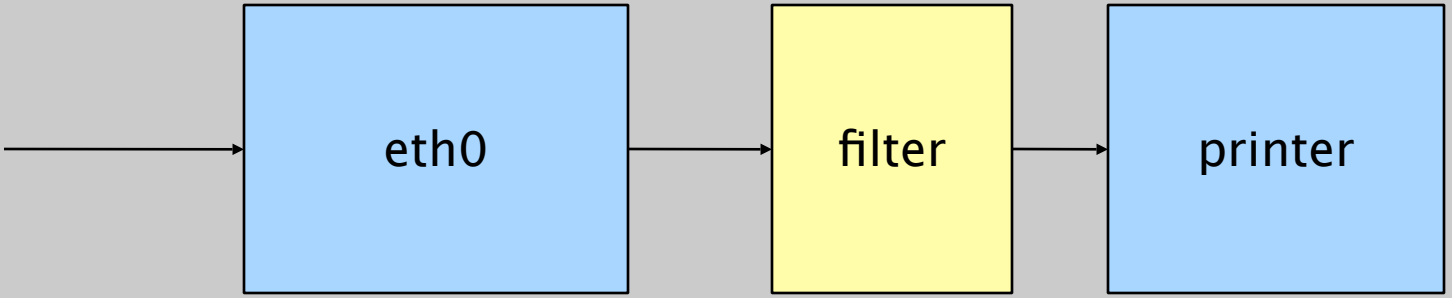
One input
executes closure
with each packet received

Example: simple-sniffer


```
let eth0 = make(<ethernet-interface>, name: “eth0”);
connect(eth0, make(<summary-printer>));
toplevel(eth0);
```

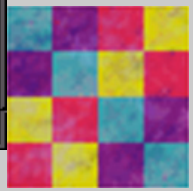
```
hannes@localhost:~
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 945 -> 57014
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 244 -> 57015
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 1413 -> 57016
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 877 -> 57017
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 532 -> 57018
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 404 -> 57019
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 16959 -> 57020
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 1030 -> 57021
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 4333 -> 57022
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 165 -> 57023
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 582 -> 57024
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 739 -> 57025
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 1214 -> 57026
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 957 -> 57027
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 290 -> 57028
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 1987 -> 57029
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 557 -> 57030
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 305 -> 57031
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.29 DST 192.168.1.35/TCP AR port 27000 -> 57032
ETH 00:0D:60:B1:E5:C8 -> 00:13:49:06:41:4E/IP SRC 192.168.1.35 DST 213.73.91.42/TCP AP port 64529 -> 1234
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.42 DST 192.168.1.35/TCP A port 1234 -> 64529
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/IP SRC 213.73.91.42 DST 192.168.1.35/TCP AP port 1234 -> 64529
ETH 00:0D:60:B1:E5:C8 -> 00:13:49:06:41:4E/IP SRC 192.168.1.35 DST 213.73.91.42/TCP A port 64529 -> 1234
```

Example: simple-sniffer with filter

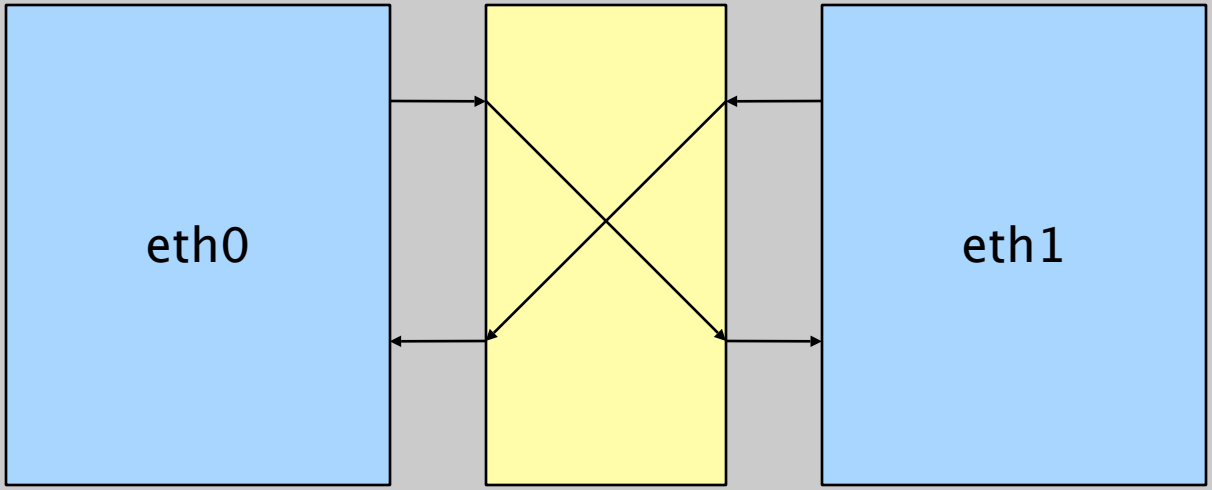



```
let eth0 = make(<ethernet-interface>, name: “eth0”);
let filter = make(<frame-filter>, frame-filter: “arp”);
connect(eth0, filter);
connect(filter, make(<summary-printer>));
toplevel(eth0);
```

```
hannes@localhost:~
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.97 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.98 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.99 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.100 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.101 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.102 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.103 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.104 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.105 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.106 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.107 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.108 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.109 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.110 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.111 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.112 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.113 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.1 tell 192.168.1.35
ETH 00:13:49:06:41:4E -> 00:0D:60:B1:E5:C8/ARP 192.168.1.1 IS-AT 00:13:49:06:41:4E
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.2 tell 192.168.1.35
ETH 00:50:8B:4C:85:3C -> 00:0D:60:B1:E5:C8/ARP 192.168.1.2 IS-AT 00:50:8B:4C:85:3C
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.3 tell 192.168.1.35
ETH 00:0D:60:B1:E5:C8 -> FF:FF:FF:FF:FF:FF/ARP WHO-HAS 192.168.1.5 tell 192.168.1.35
```

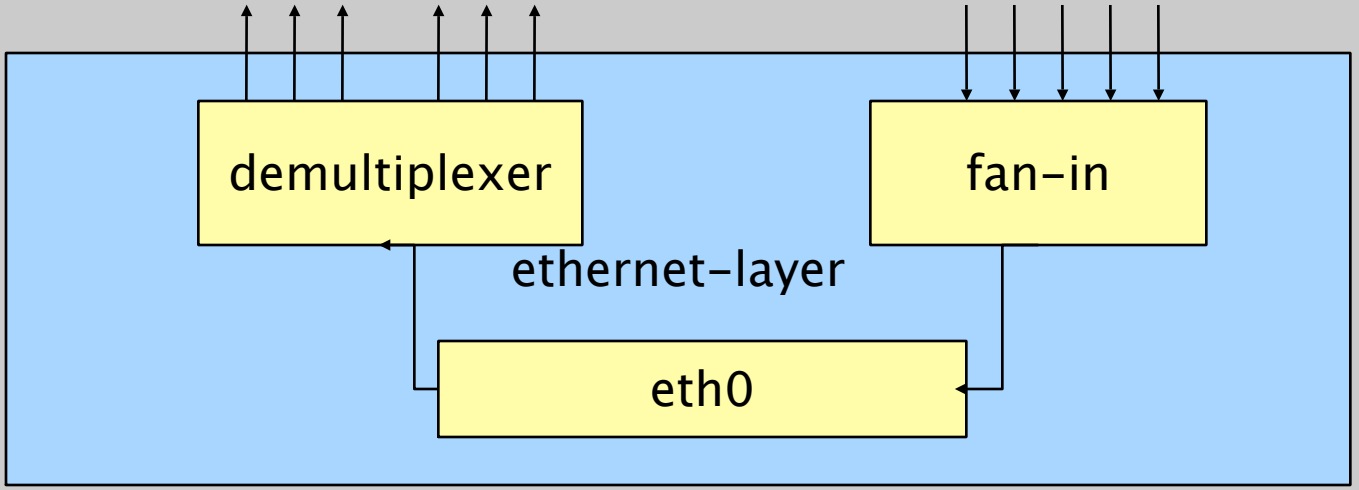


Example: bridge

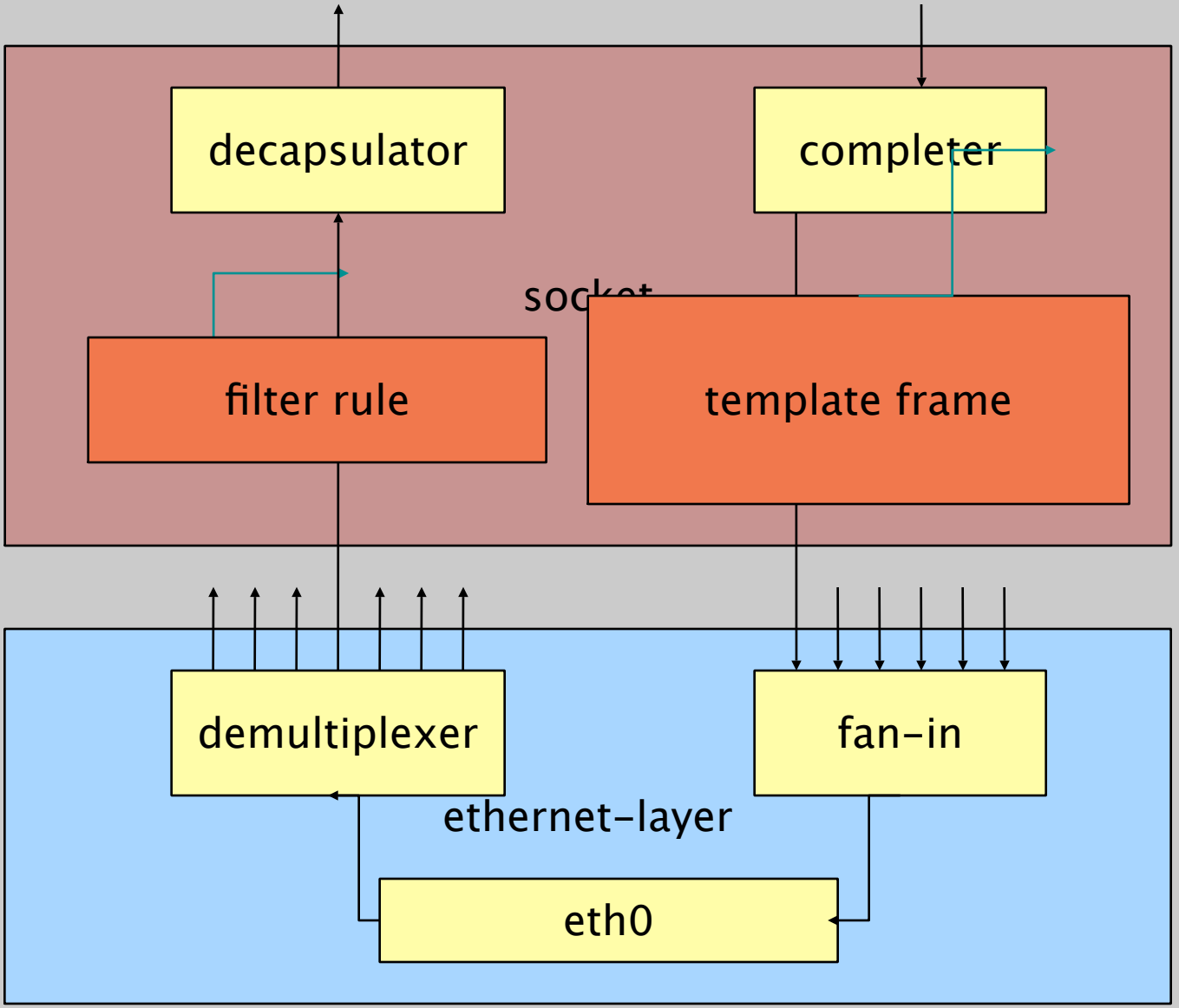



```
let eth0 = make(<ethernet-interface>, name: “eth0”);
let eth1 = make(<ethernet-interface>, name: “eth1”);
connect(eth0, eth1);
connect(eth1, eth0);
make(<thread>, function: curry(toplevel, eth0));
make(<thread>, function: curry(toplevel, eth1));
```

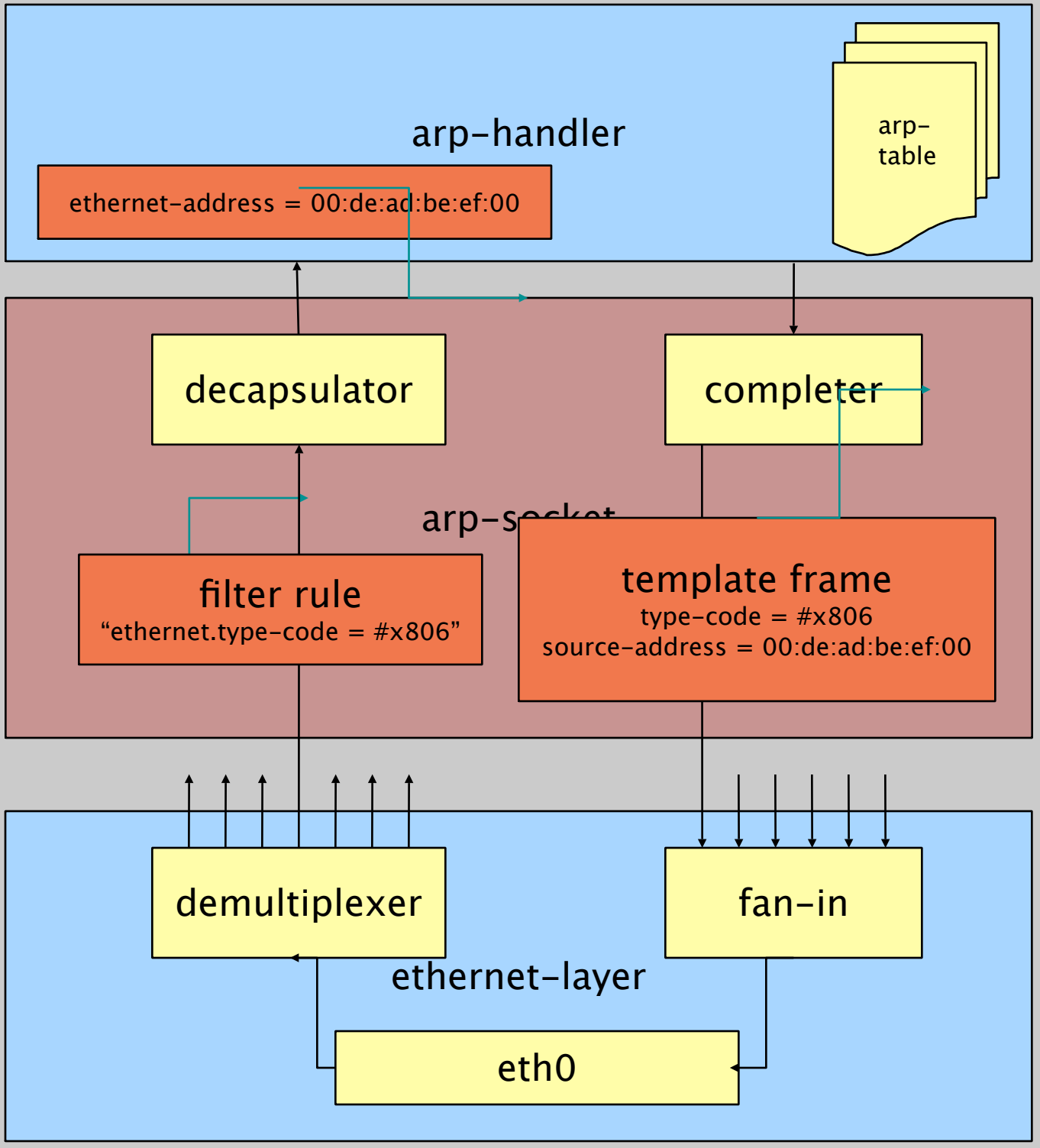
Layering – ethernet layer



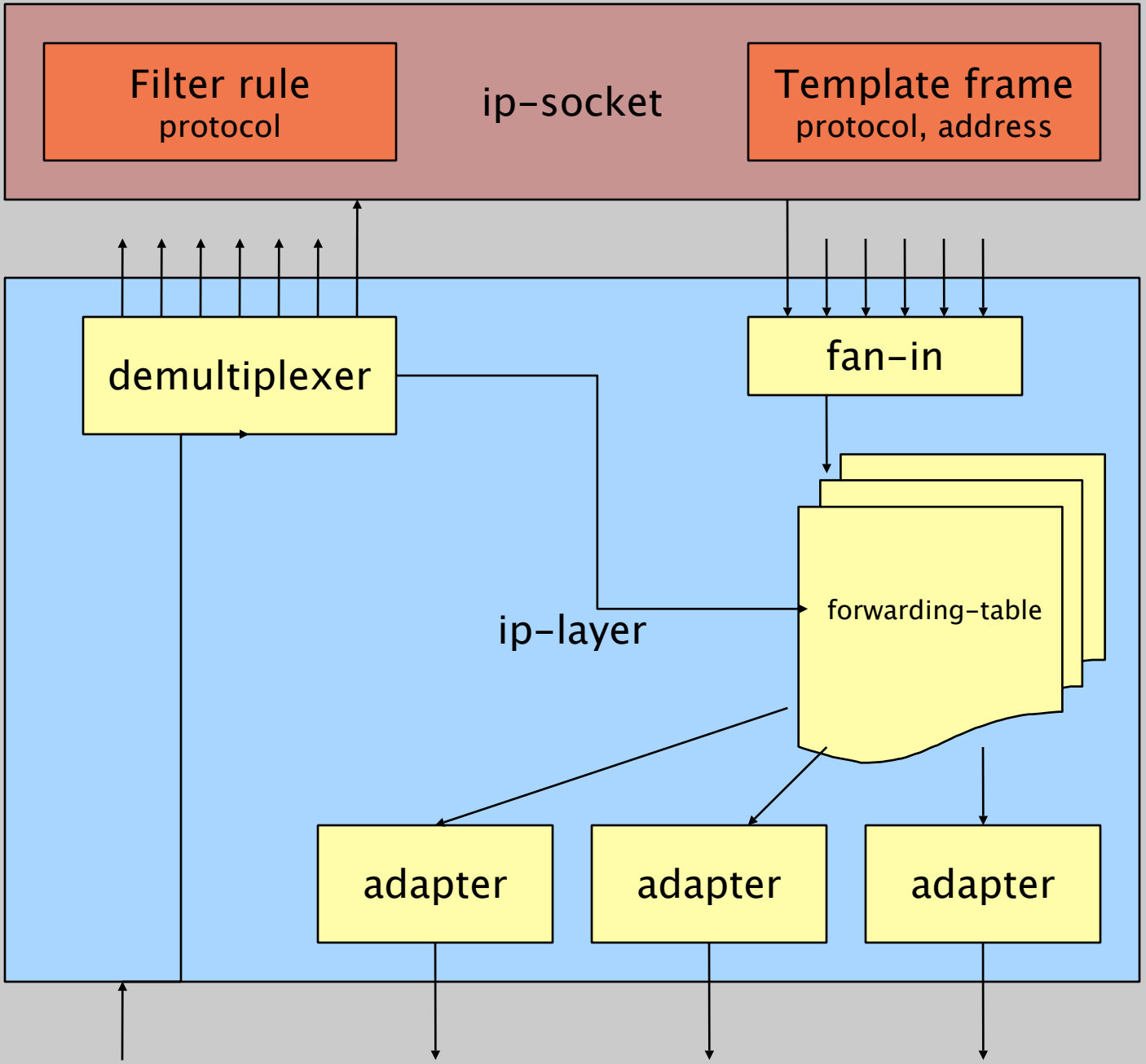
Layering - Socket



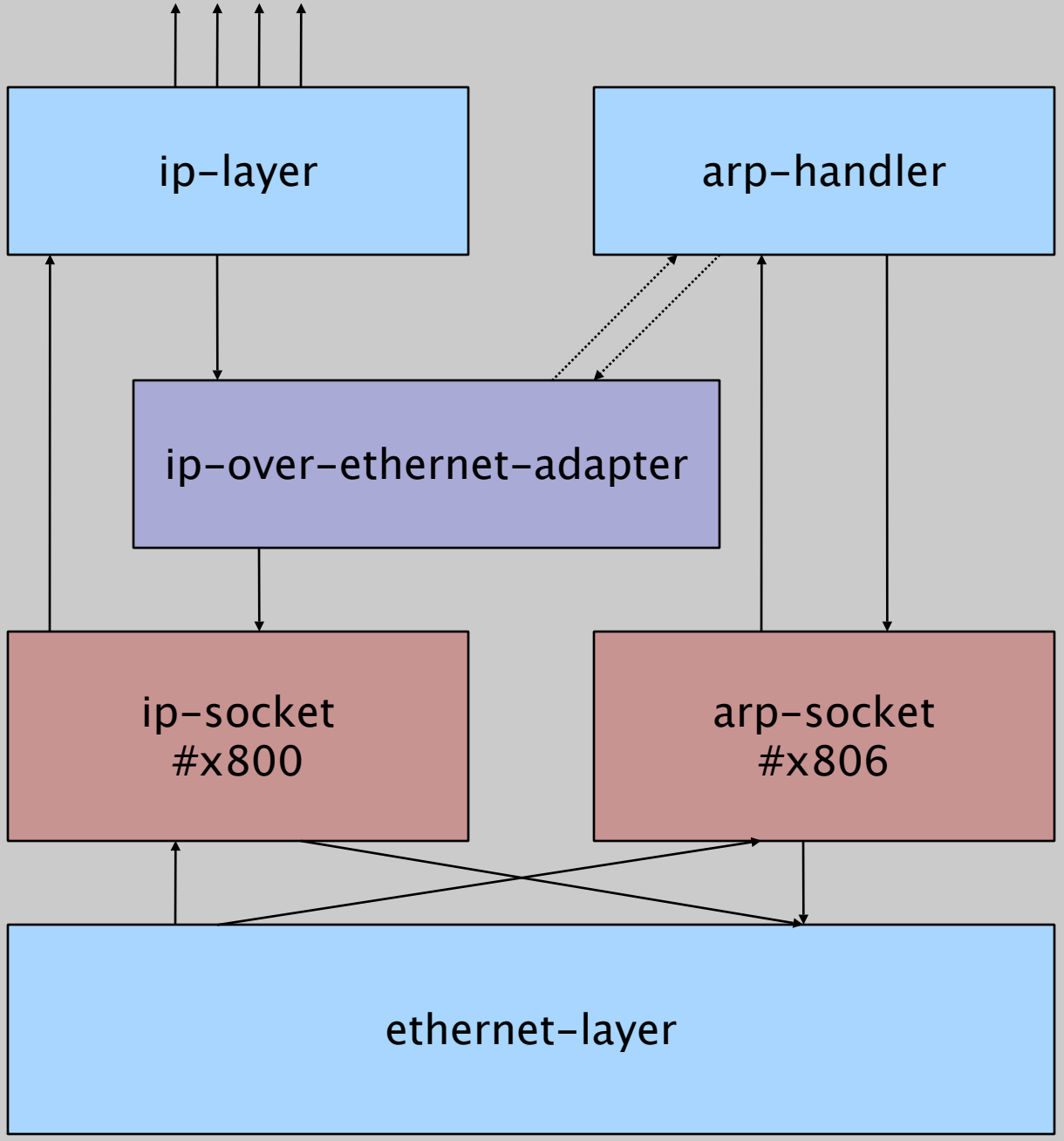
ARP


arp-handler
arp-table
ethernet-address = 00:de:ad:be:ef:00
decapsulator
completer
arp-socket
filter rule
"ethernet.type-code = #x806"
template frame
type-code = #x806
source-address = 00:de:ad:be:ef:00
demultiplexer
fan-in
ethernet-layer
eth0

IP


Filter rule
protocol
ip-socket
Template frame
protocol, address
demultiplexer
fan-in
forwarding-table
ip-layer
adapter
adapter
adapter

IP-over-ethernet Adapter



Applications

- Protocols currently supported
  - Ethernet, IPv4, TCP, UDP, DNS, 802.11, ARP, pcap, STP, DHCP, ID3v2
- Secure Network Services
  - dns-server, http-server, etc. pp.
- Firewall
- Network Night Vision
- Intrusion detection Systems

Conclusion

- Software Architecture is Software Security
- IP Stack without remote exploits

Announcements

- http://www.networknightvision.com
- Dylan Hackers Conference Europe 2006
- 15:30 - 17:00 Dylan Introduction Workshop
- 21:30 - 23:30 packetizer workshop

Links

- Dylan Website http://www.opendylan.org
- Software Security is Software Reliability http://doi.acm.org/10.1145/1132469.1132502
- Click http://www.read.cs.ucla.edu/click/
- Scapy http://www.secdev.org/projects/scapy/
- Conduit+: A Framework for Network Protocol Software
  - Hueni, Johnson, Engel, OOPSLA '95
- Code: svn://svn.opendylan.org/scm/svn/dylan/trunk/libraries
  - (especially packetizer, sniffer, flow, layer)