The Evolution of IPsec

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Topics

- What is IPsec?
- How did it evolve? Why is it the way that it is?
  - Origin
  - Technical constraints
  - Organizational, political, and other non-technical issues
- Yes, non-technical issues matter…

What is IPsec?

- Encryption at the IP packet layer
- Protect *all* packets, without changing applications
- Must conform to the IP service model:
  - Stateless—each packet stands by itself
  - Packets may be dropped, duplicated, damaged—correctness is end-to-end, i.e., handled by the transport layer (TCP)
  - But: at the *network* (IP) layer
  - Network layer encryption can protect all packets, even those from naive applications

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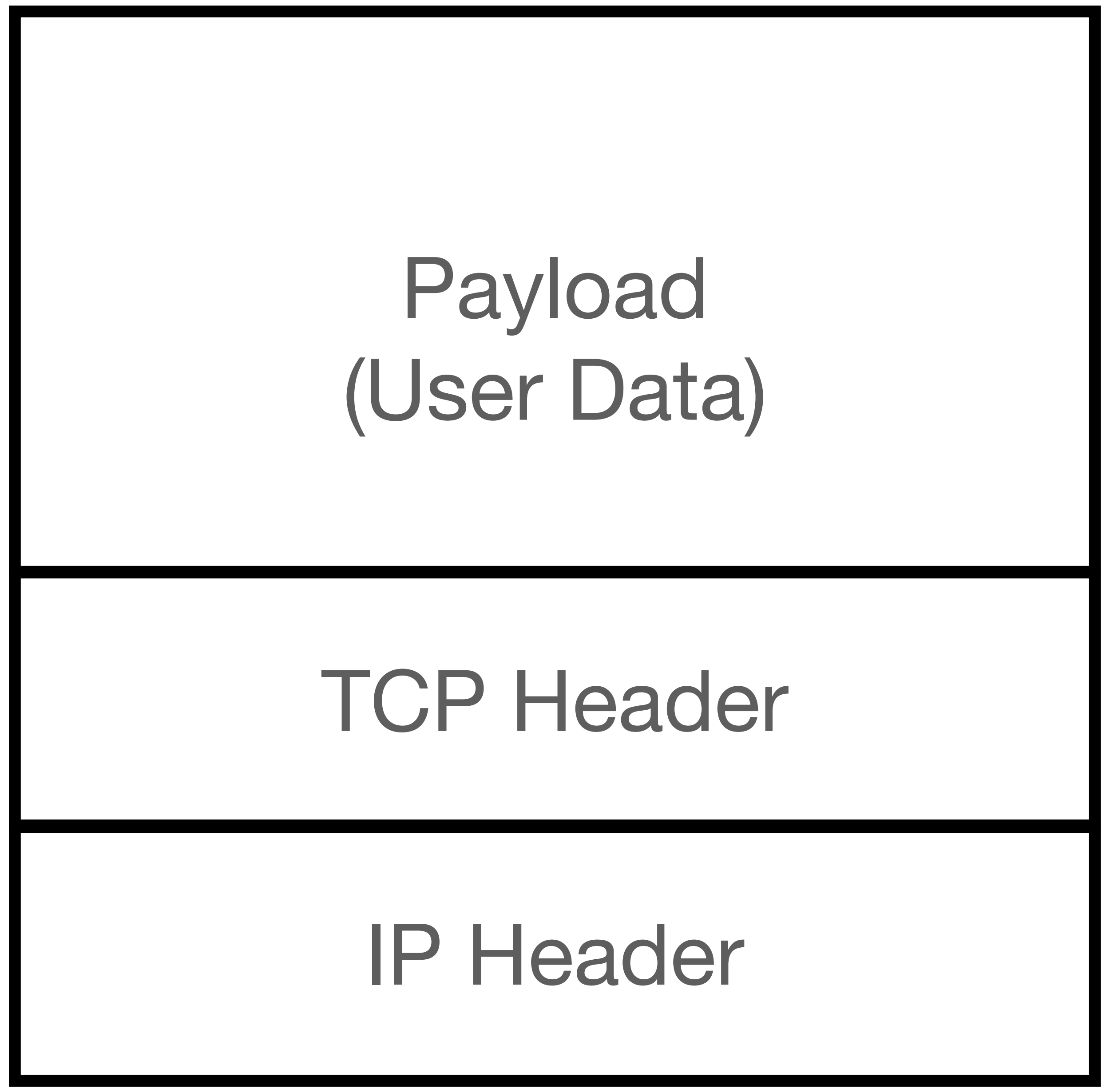
Quick IP Refresher

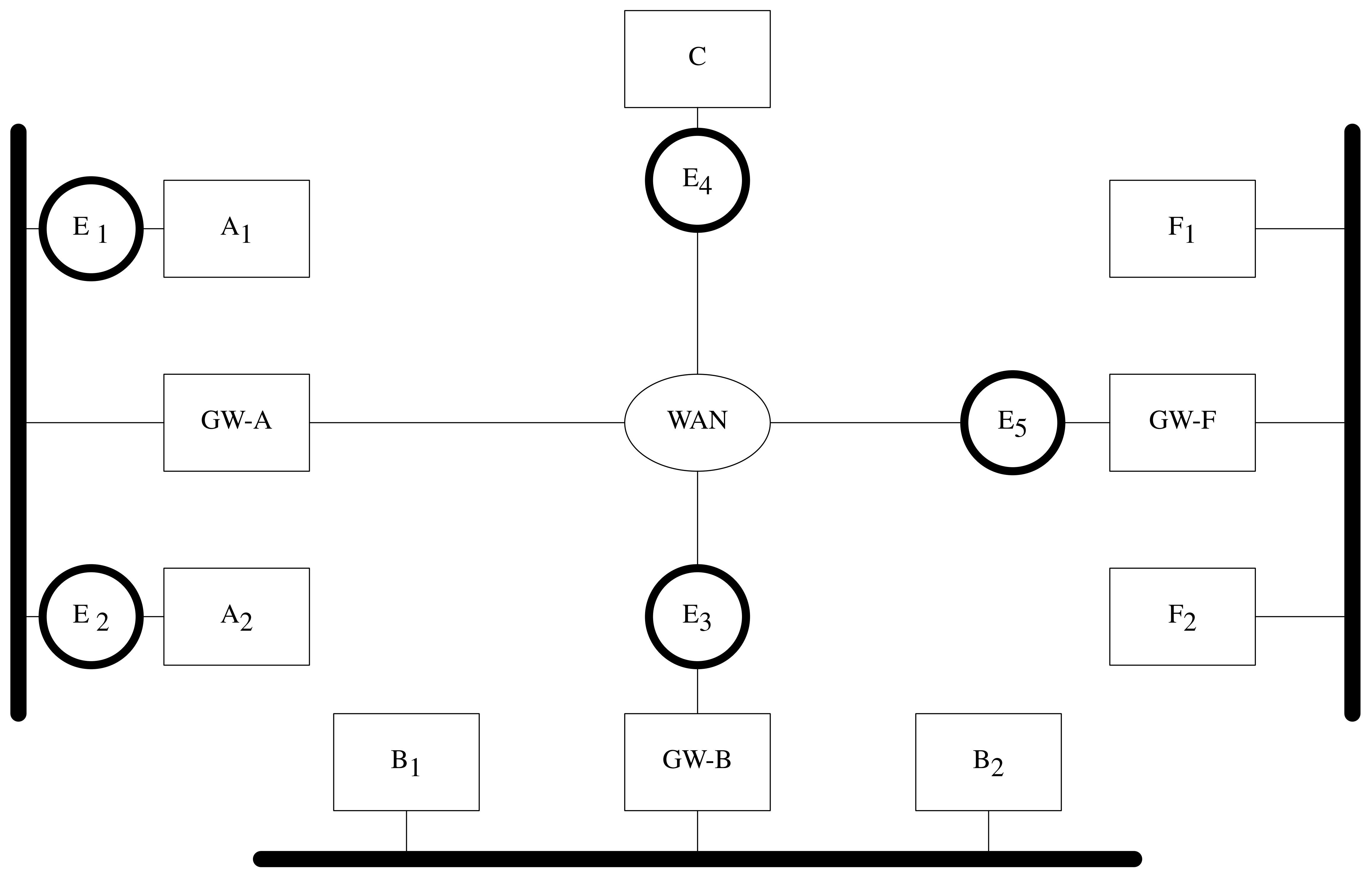


- The IP header is used to route the packet to the destination
    - It contains source and destination IP addresses, plus a “next protocol” indicators
- The TCP header contains port numbers, a checksum, and sequence number data
- Packets may be lost, damaged, duplicated, delayed, replicated, delivered out of order, etc.

Operational Scenarios

- End-system to end-system
- End-system to gateway (firewall)
- Gateway to gateway

Topologies



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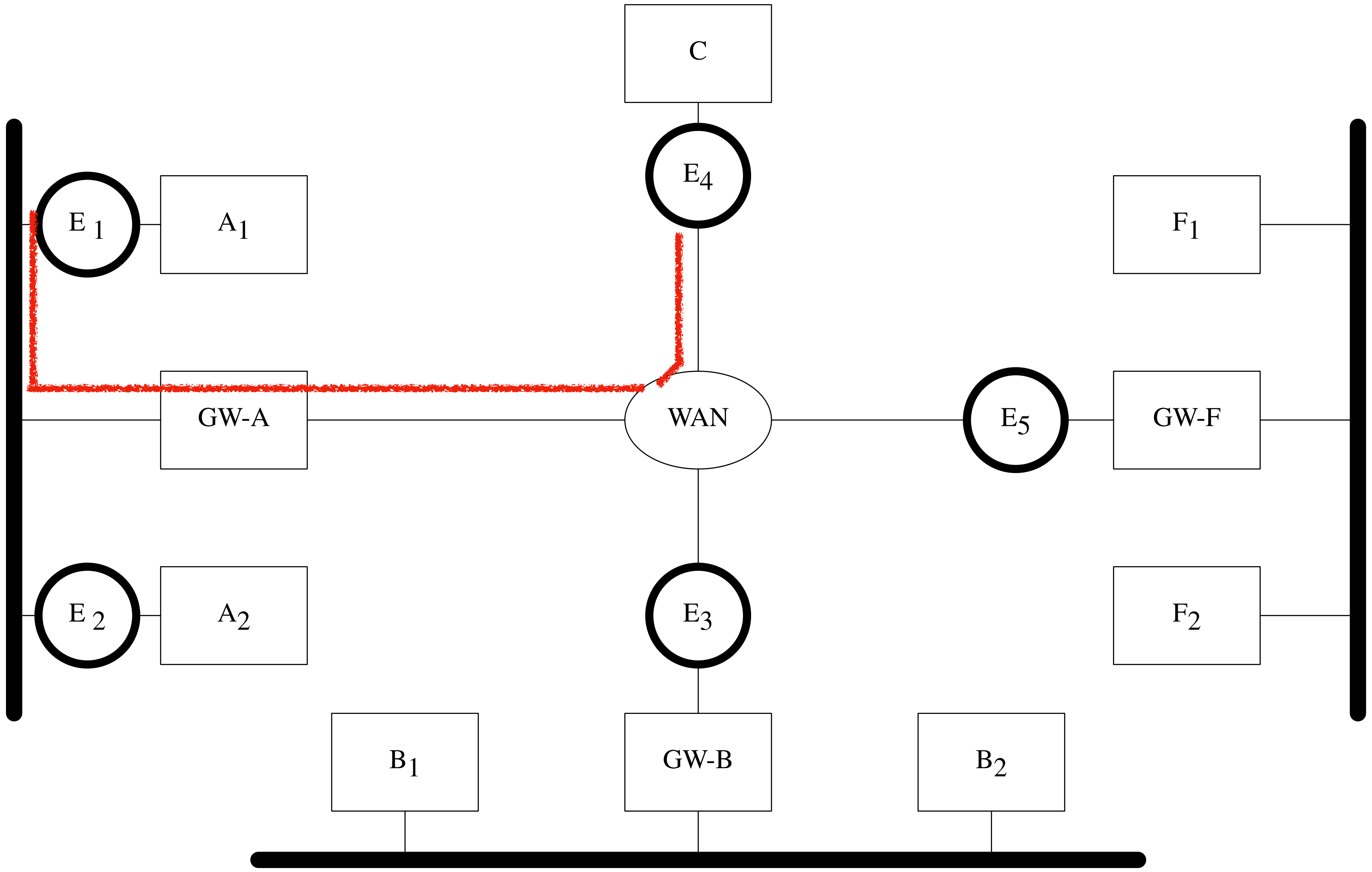

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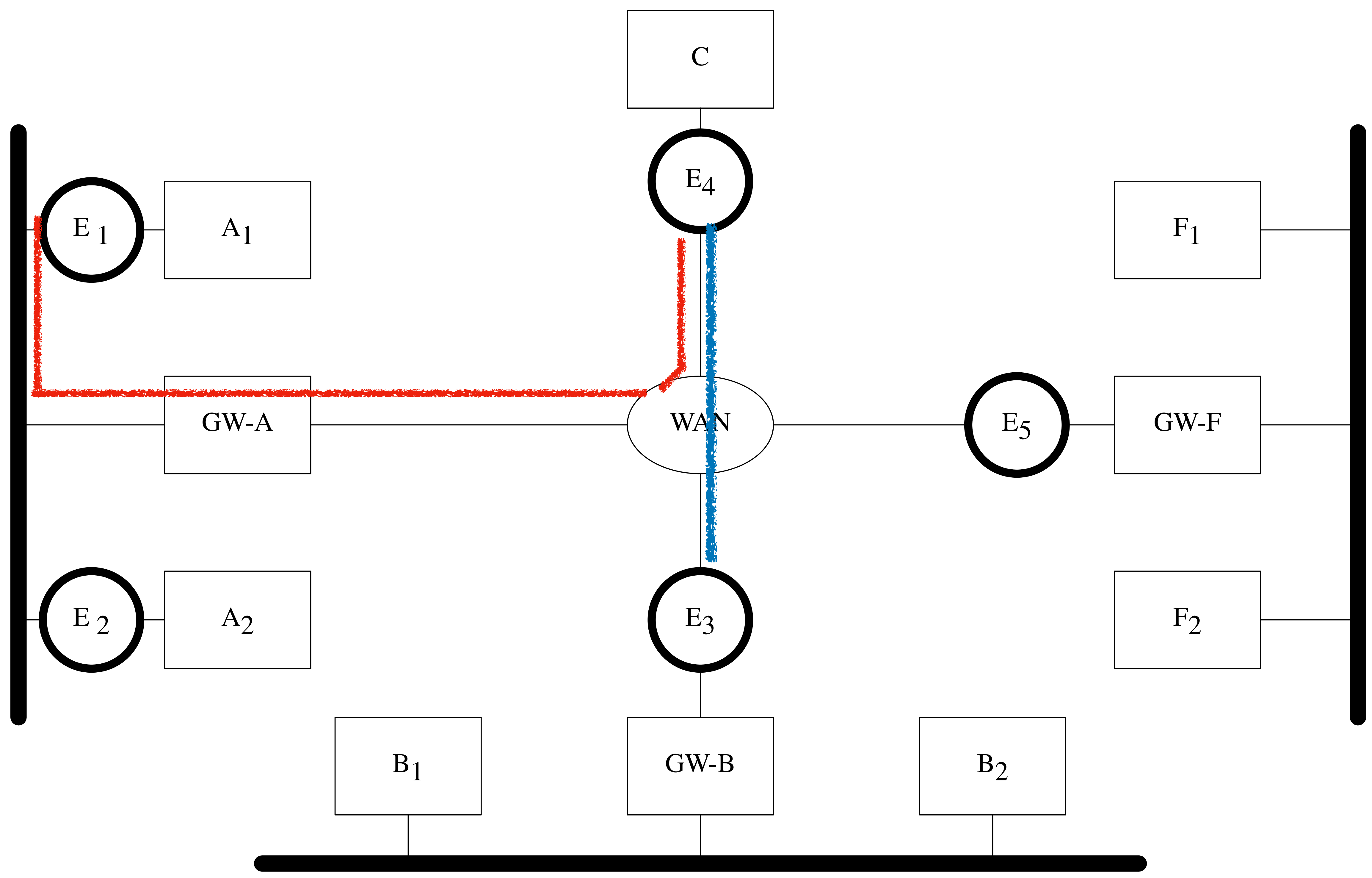

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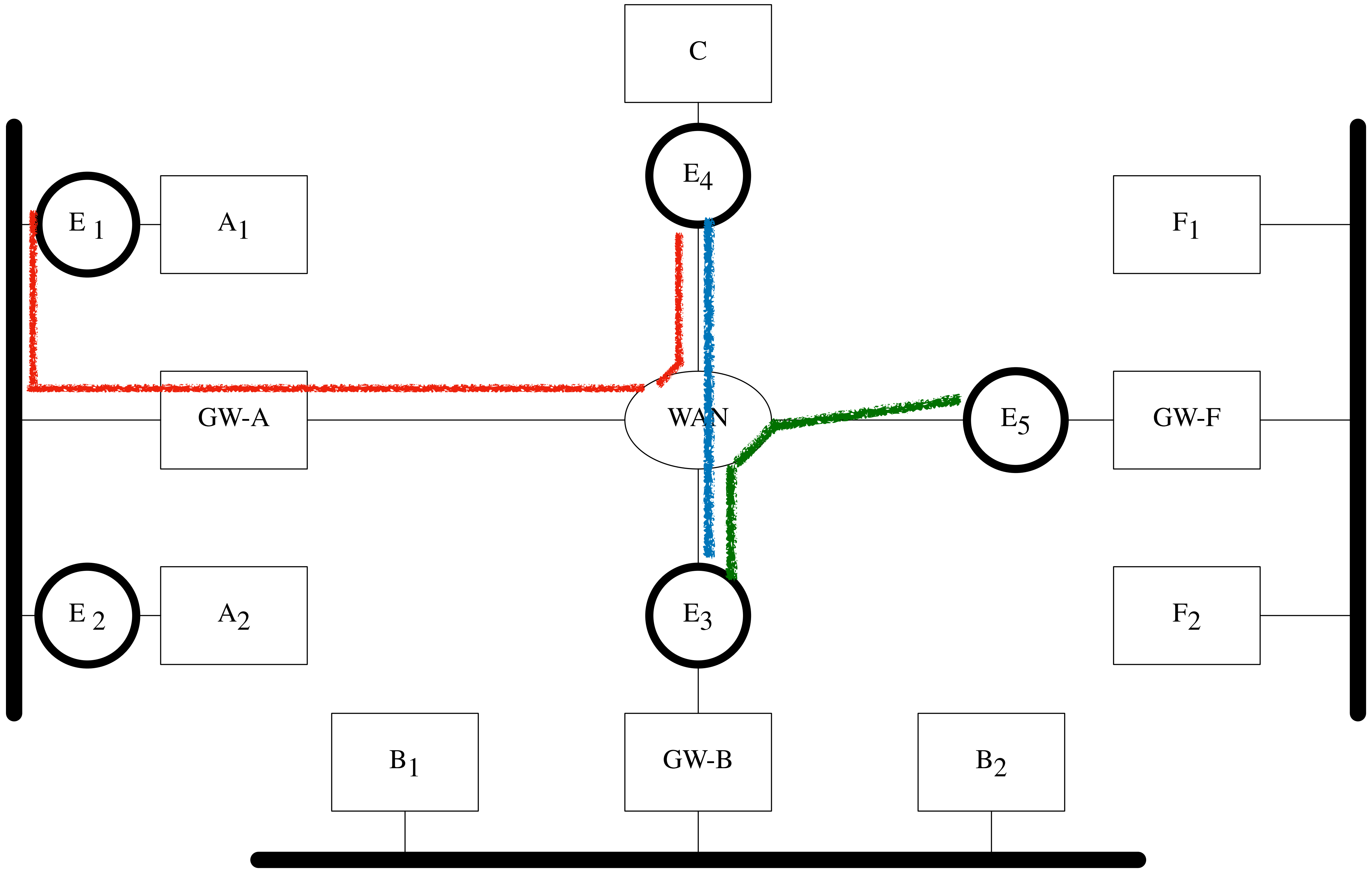
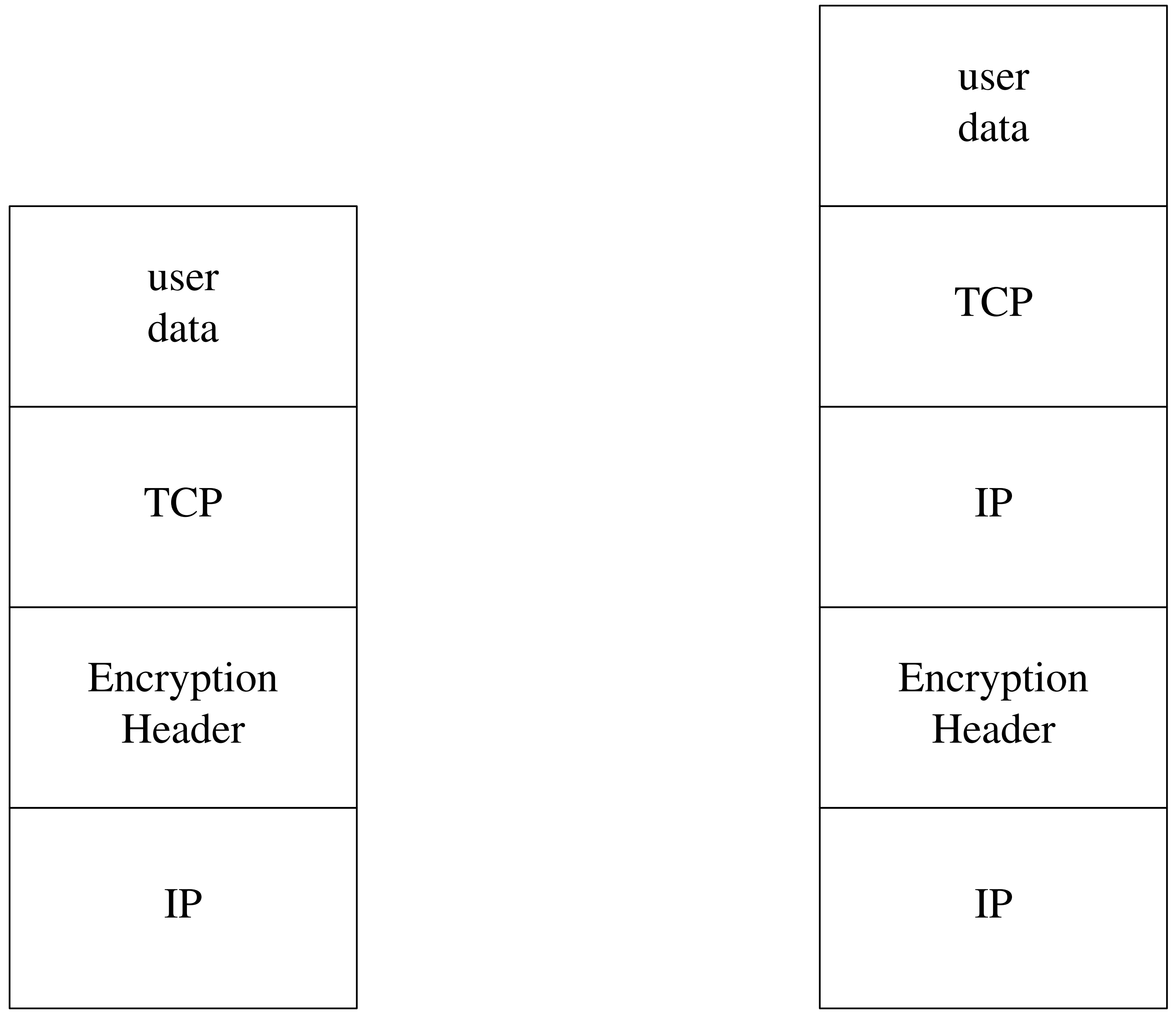


Generic Structure



End System
to
End System

Encryptor
to
Gateway

SP3: Early Network-Layer Encryption

- Part of DoD’s Secure Data Network System
- Interesting points:
  - SP3 supported OSI and IP (“DoD Internet”) protocols
  - OSI terminology (PDU, NSAP, etc.)
  - Military terminology: “red” and “black” nets
  - Confidentiality and integrity checks are both optional services
  - Variable-length fields

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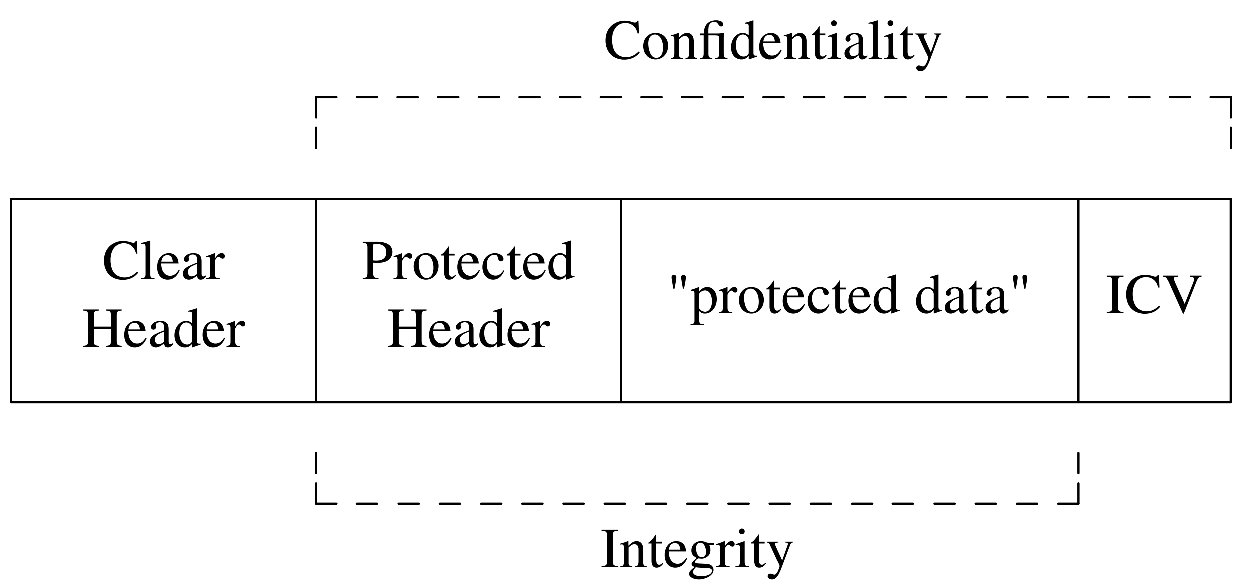
SP3: Packet Format

SP3



Clear Header

Length	SE (type)	KEY_ID
1	1	var

Protected Header

Length	Flags	Pad	IP Header
1	1	var	var

Integrity and Confidentiality

- The “protected header” is *always* integrity-protected—necessary for access control
- Integrity only—for export control reasons?
- Confidentiality only—especially when this was designed, cryptographic processing was *expensive*: eliminate integrity checks on high-speed, bulk transmissions that could tolerate occasional bit errors (e.g., video in OFB mode)
- *No* details are given for the cryptographic algorithms

Interesting Aspects

- Cryptographic details—algorithm, block size, length of ICV, etc.—are all identified by the KEY_ID. (Why?)
  - KEY_IDs specify permissible source and destination addresses—used for access control
  - Address format linked to KEY_ID
  - Key negotiation is handled externally
- The flag field only indicates the direction of the packet—prevent reflection attacks
  - Both directions of a connection might share the same KEY_ID, though they didn't have to
- Padding here *can* be used to align the IP header to a 4-byte boundary

Key Management

- Separate policy from mechanism
- Slower and more complex, but also done much less often
    - Put per-packet encryption in the kernel; do key management at user level
    - Actually, per-packet encryption can be done outboard, in hardware
    - Allow for complex policies, CRLs, etc.
    - Negotiate multiple keys: different directions, integrity versus confidentiality, etc.
    - Forward secrecy

Policies

- Encryption and/or integrity protection
- What should be encrypted on transmission?
  - By destination IP or net address? (By host name?)
  - Port numbers?
- What should have been encrypted on receipt
- Algorithms, e.g., open or NSA Type 1?
  - Key lifetimes, in seconds or bytes
- Address of decryptor

Ioannidis and Blaze: swIPe (1993)

- Simplification of SP3
  - Eliminate most options
  - Internet-only—no OSI support
- But: a sequence number is added “to protect against replay”
  - Huh? The IP service model permits packet duplication—is this needed?
  - No further explanation given
- Freely available running code for two popular Unix variants

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Enter IPsec

- An IETF Working Group
- Goal: an Internet standard for packet-level encryption
- A descendant of SP3 and swIPe—the designers of IPsec were very familiar with both
    - The designers of swIPe were part of the IPsec process
- An Internet standard has to have more generality, and hence more options, than swIPe
    - Example: must support multicast and MobileIP

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Desiderata

- (Availability of) ubiquitous network-layer encryption
  - Network layer, because that would protect all traffic, even that of naive applications
  - “Availability of” because computers were too slow then to encrypt everything—but we knew they’d get faster
  - We wanted to replace address-based authentication
- Security policy “selectors” would include IP addresses, host names, port numbers, and usernames
  - My traffic could be protected differently than yours
- Multiple granularities of encryption: network pair, host pair, per-user, per-connection

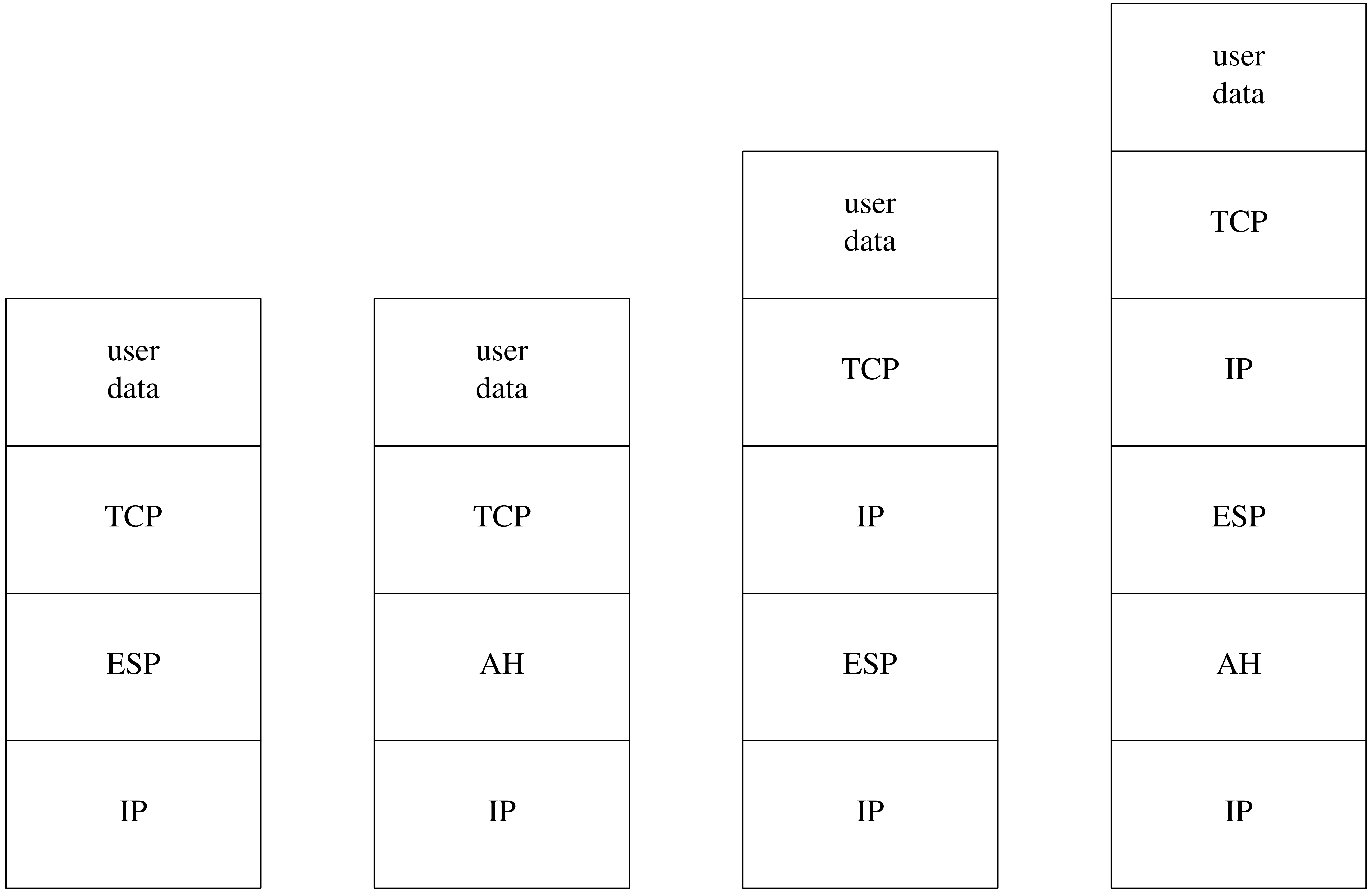
Constraints

- US export controls on cryptography
  - You needed a license to export confidentiality technology; authentication technology was not restricted
- Limited cryptographic state of the art
- Designers had somewhat limited cryptographic knowledge

RFC 1825 Architecture

- Separate confidentiality (ESP) from authentication (AH)
- Explicit “transport” versus “tunnel” mode, similar to SP3
- Have a separate key management/policy protocol—but it was never defined
- Relied on SPI—security parameter index—that serves the same role as the KEY_ID in SP3
- Unlike swIPe, no sequence numbers

Packet Layouts

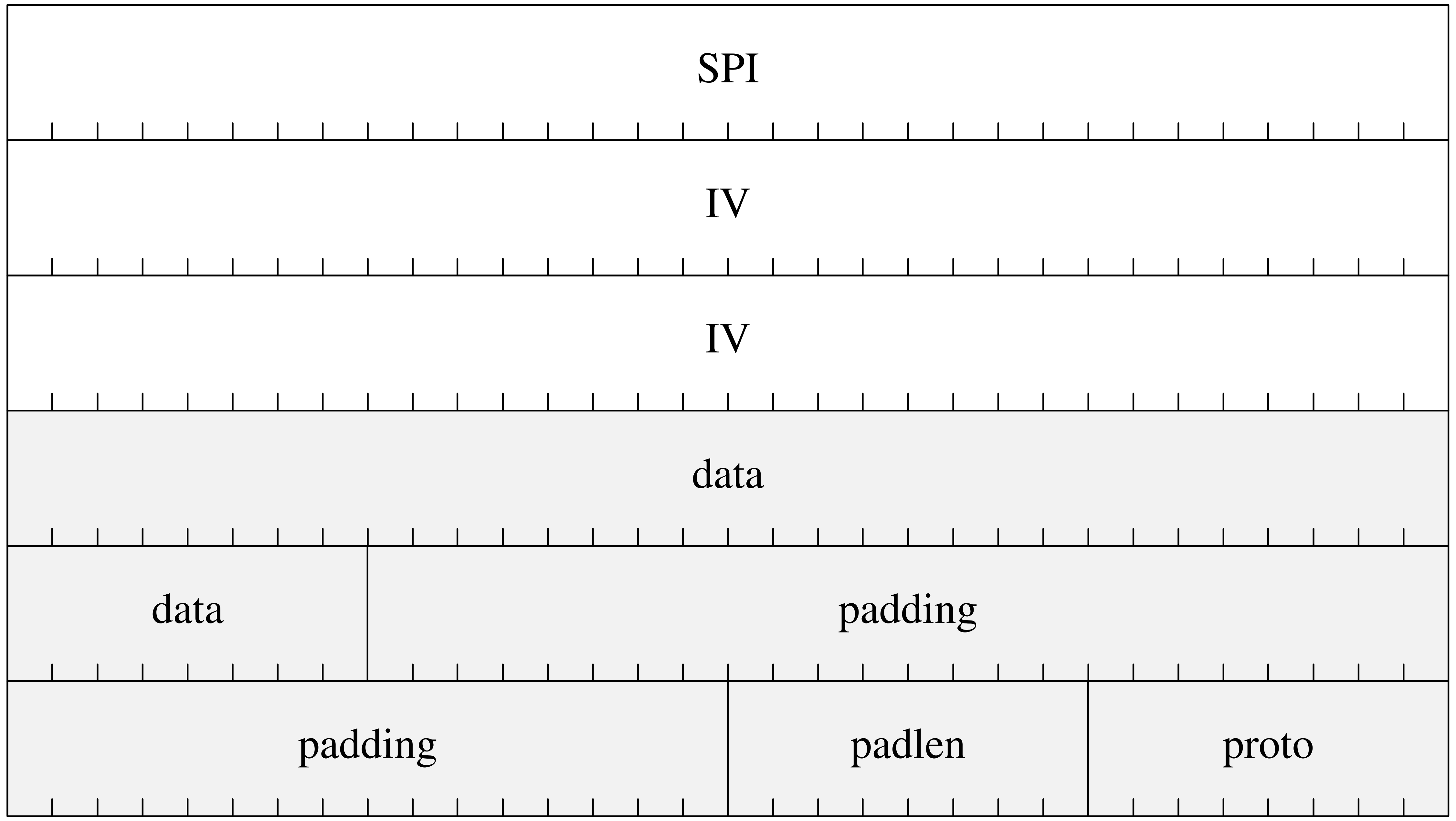


The IPsec SPI

- Random
- Separate SPI for each direction
  - No need for SP3's flag
  - In theory, harder to link traffic in opposite directions, since the SPIs don't match
  - Is it a problem in practice?
- Bound to a source/destination address pair

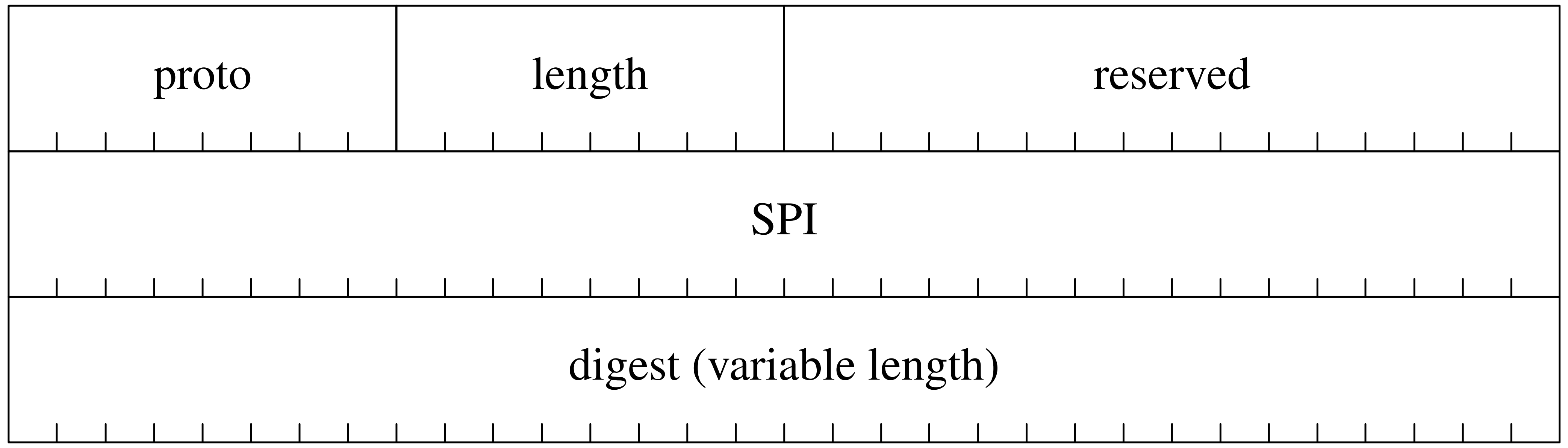
Confidentiality: ESP

- The pair <dest_IP, SPI> identified the key and parameters
  - Multicast packets shared a multicast destination IP address
  - Also need SPI for rekeying
- Padding was for cipher block size—but could also be increased to (try to) defeat traffic analysis
- (IV shown is 8 bytes, for DES)
- (Shaded portion is encrypted)
- ESP use was *optional*



Integrity: AH

- Similar SPI definition
- The AH header covered not just the remainder of the packet but also *part* of the preceding IP header, e.g., the source and destination addresses and *some* IP options
    - Layering violation—and made implementations very messy!
    - N.B.: some parts of the IP header change en route
- Use of only AH was export-friendly and permitted firewalls to inspect packets without knowing a key
- AH was *optional*—integrity check could be omitted



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Other Issues

- Sequence numbers—were they needed?
  - Matt Blaze said “yes”, because of replay attacks
  - I said “no”, because IP had to handle packet duplication anyway
  - I won…
- Some people wanted RC4 for encryption—much faster
  - RC4 is a stream cipher, which *must not* be used with manual key management (though WEP did it…)
  - But there was a strong desire to support manual keying
- Many people disliked AH because of its layering violations

Key Management for IPsec

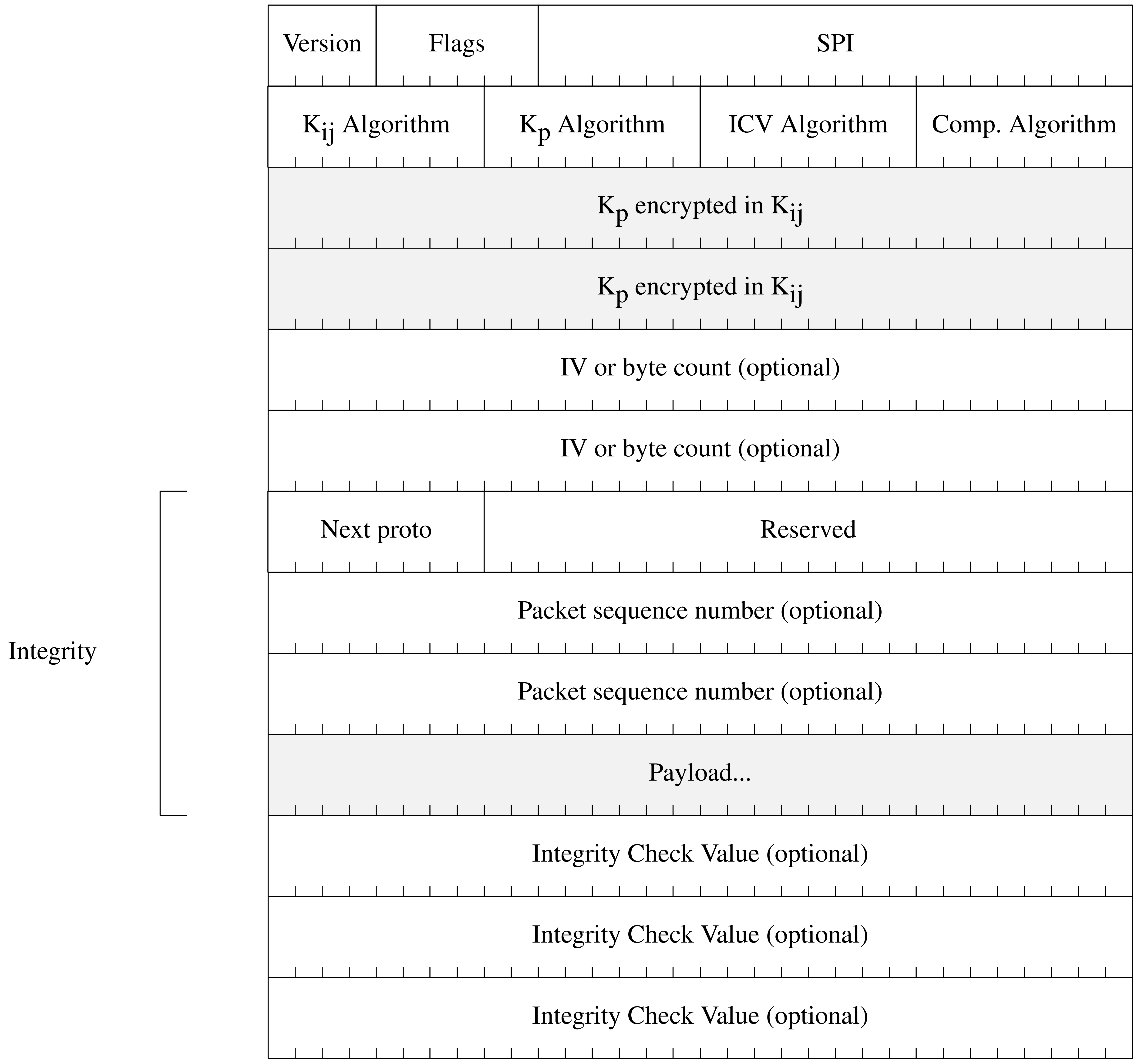
- Basic framework proposal: ISAKMP, from the NSA
  - The IETF added the cryptography (called IKE): roughly speaking, an RSA-signed dialog with optional Diffie-Hellman exchange for forward secrecy
  - There was another protocol proposed, Photuris
- ISAKMP/IKE is *horribly* complex
  - Includes session management as well as key negotiation
  - Had many different modes, phases, authentication schemes, etc.
  - No time for a thorough treatment of it—but it was a disaster (and had serious functionality bugs)

SKIP: The Road Not Taken

- IP is a stateless datagram protocol
- ESP/AH (and SP3 and swIPe) require key negotiation and setup—and that requires state
  - It's no longer a pure datagram protocol
  - That's why ISAKMP has session management: when are keys deleted?
- SKIP was a stateless alternative

SKIP Design

- Agree on a Diffie-Hellman modulus *p* and base *g*
- Each node *i* has a certificate for its DH half-key: g^i mod *p*
- The key K_{ij} for traffic between <*i,j*> is g^{ij} mod *p*
- Use that key to create a traffic key K_p — rekey after some fixed limit
- Integrity, encryption, sequence, compression are all optional (controlled by flag field)



Problems…

- The varying offsets, depending on options and algorithms, make parsing more difficult
- The algorithm identifiers are sent in the clear—might aid cryptanalysts
- Policy is less flexible; no provision for forward secrecy
- *There needed to be universal agreement on algorithms—no chance to negotiate them*
- *There needed to be universal, **permanent** agreement on Diffie-Hellman parameters*

Organizational Politics Time

- Many people preferred Photuris to ISAKMP/IKE
  - There were "personality conflicts" regarding Photuris—only ISAKMP remained
- There was a bitter split, and no consensus, over ESP/AH versus SKIP
  - SKIP was enhanced—and made more complex—to handle optional forward secrecy
- Ultimately, the working group could not decide; the Security Area Director had to call it
  - Crucial issue: *the inability to change the Diffie-Hellman parameters*
  - Sun Microsystems (which was behind SKIP) had recently had a security disaster with bad Diffie-Hellman parameters

Final Outcome

- ESP/AH won over SKIP
- Sequence numbers were deleted
- No design concessions were made to the export rules ("the Danvers doctrine")
  - Given the expense of encryption with 1995 hardware, integrity-only (i.e., AH) was a rational alternative
- Many working group members were exhausted by this time
  - ISAKMP was selected as the only choice; no one had the energy to propose an alternative

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There Were Problems…

- There were no good integrity algorithms then
  - HMAC, once invented, was a drop-in replacement
- Lack of sequence numbers was a mistake
- Lack of mandatory integrity checks was a mistake
- The suggested IV selection method for DES-CBC—a simple counter—was a mistake
- ISAKMP was a mistake
- Most of these issues had to do with lack of cryptographic expertise in the IETF's IPsec working group

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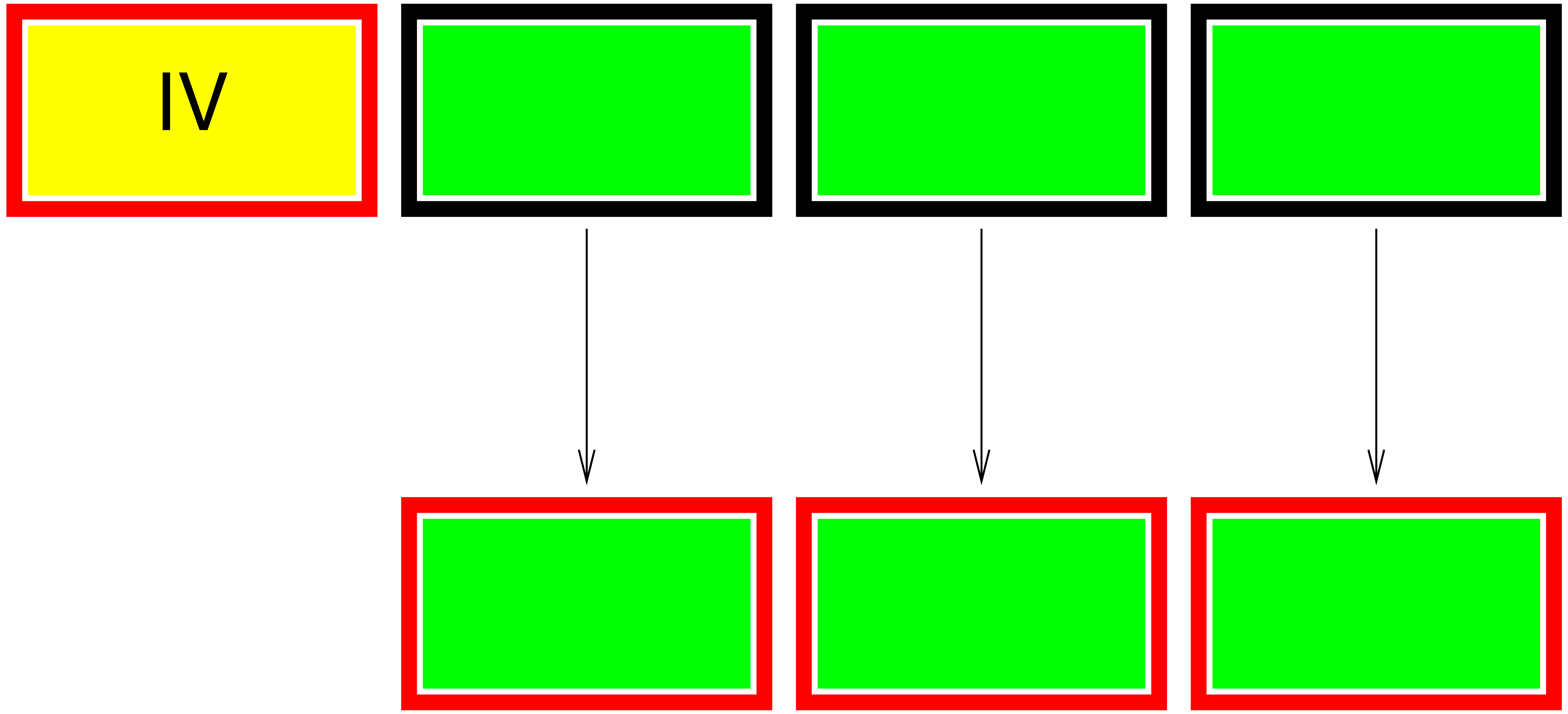
A Helpful but Misunderstood Rumor

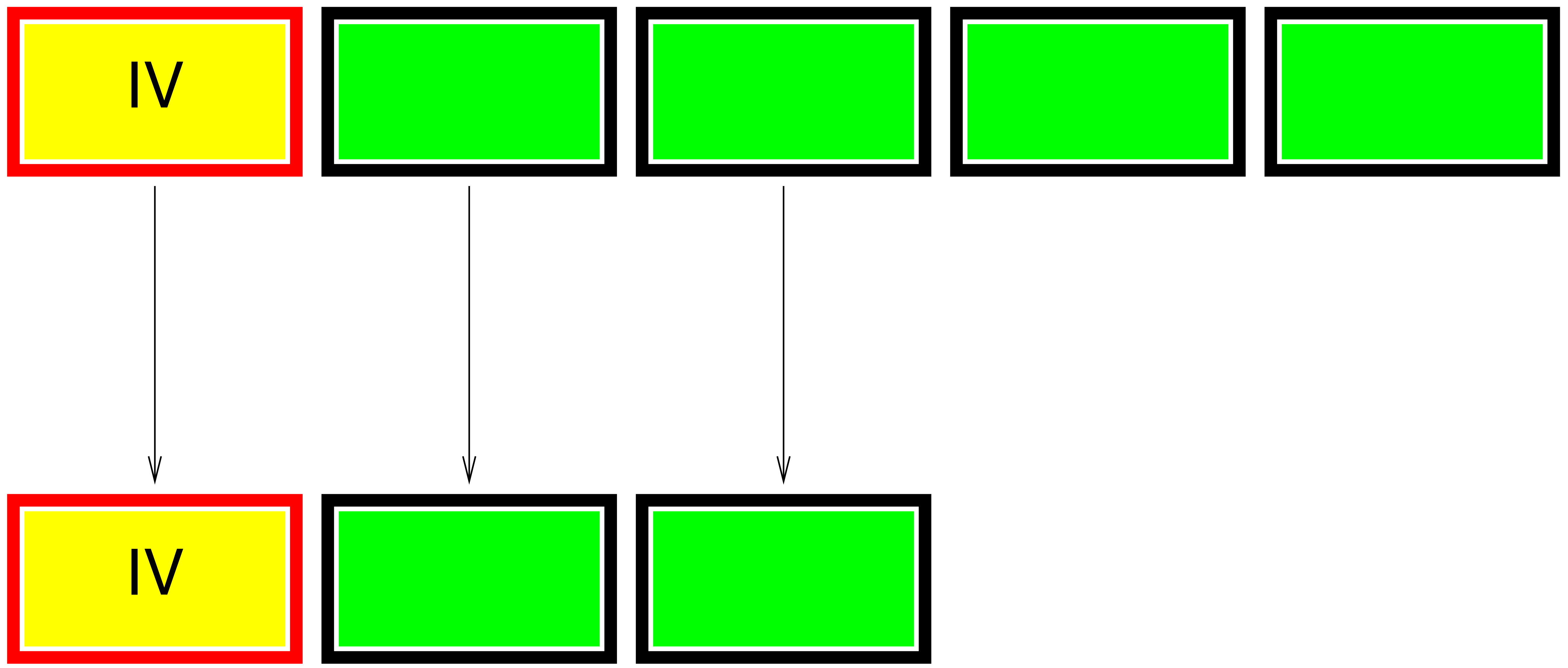
- There was a rumor floating around that the NSA could break CBC encryption
- The claim seemed obviously wrong to me—but I decided to investigate
- That was a good move…

CBC Mode

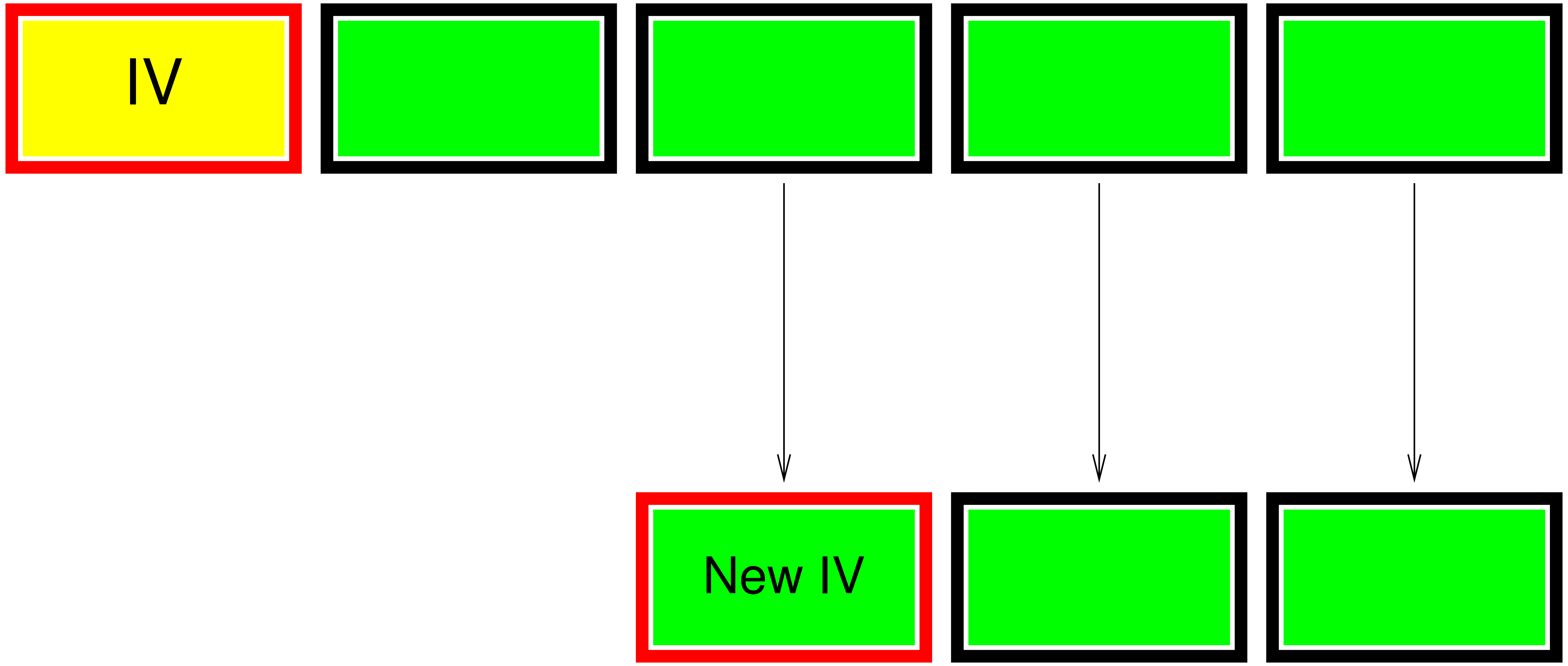


An IV plus *n* blocks of plaintext yields *n* blocks of ciphertext.
But—cutting and pasting CBC streams is interesting…

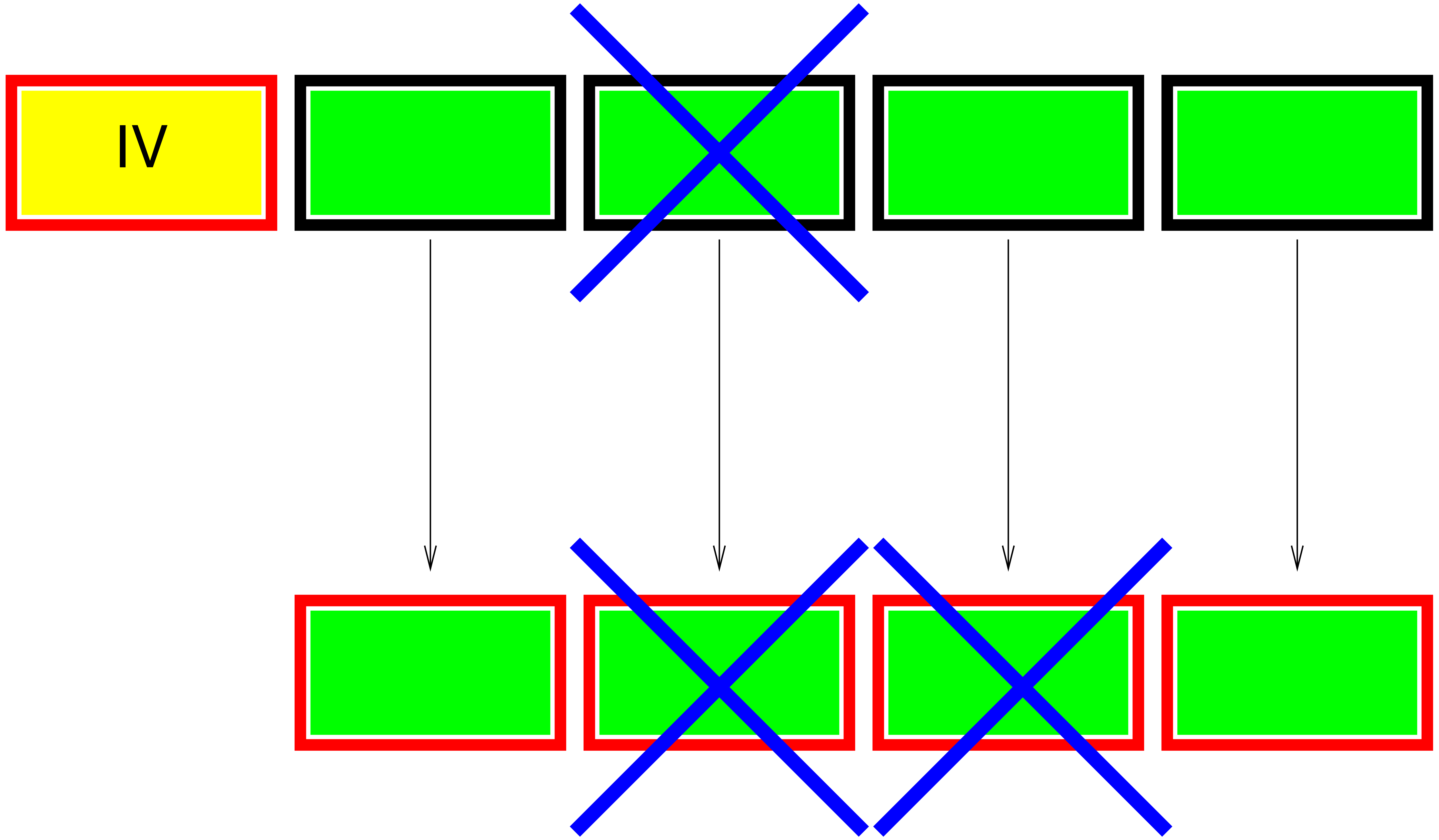
The Prefix of a CBC Message is a Valid CBC Message



The Suffix of a CBC Message is a Valid CBC Message



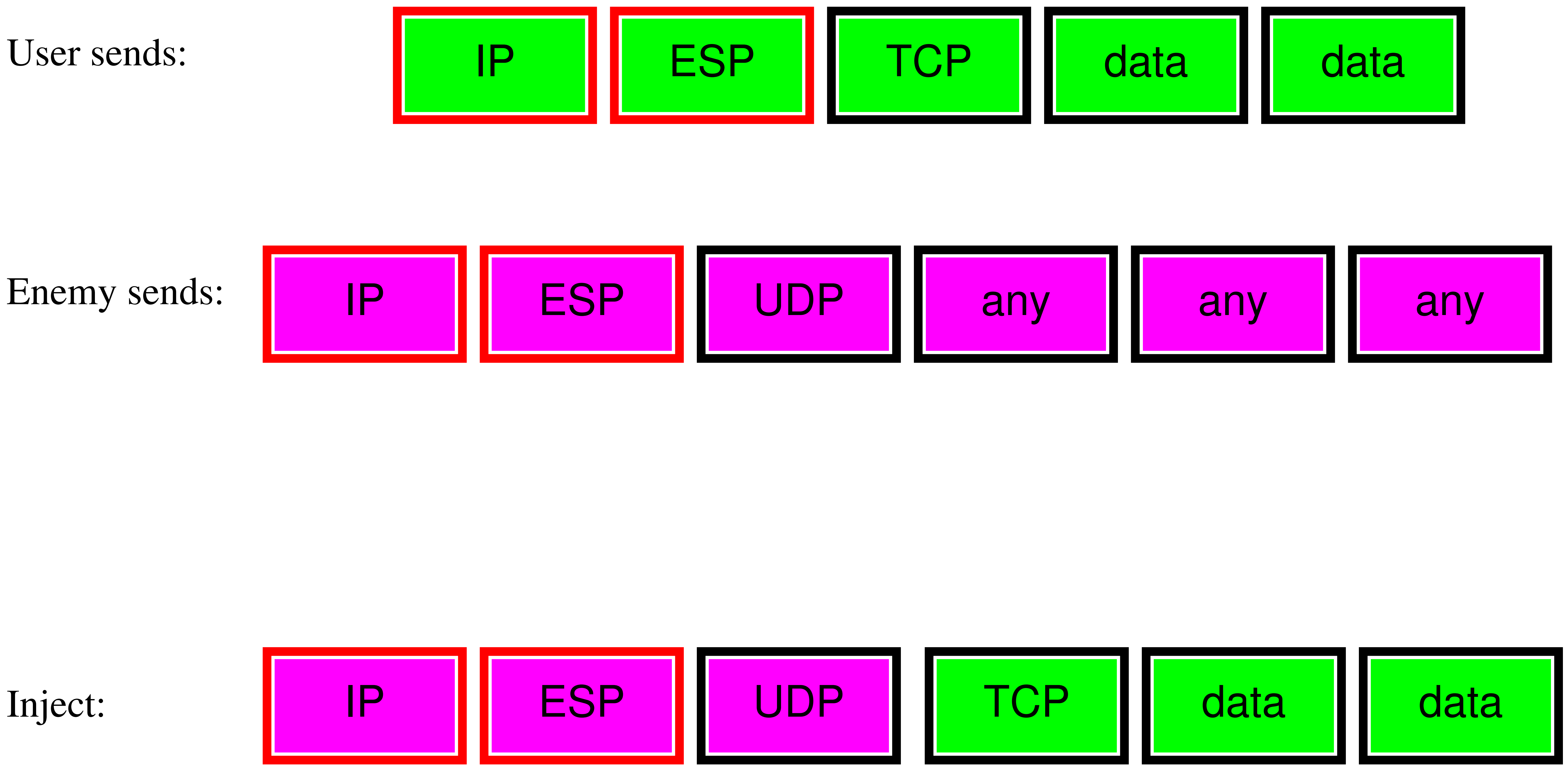
Error Propagation is Limited



Environmental Assumptions

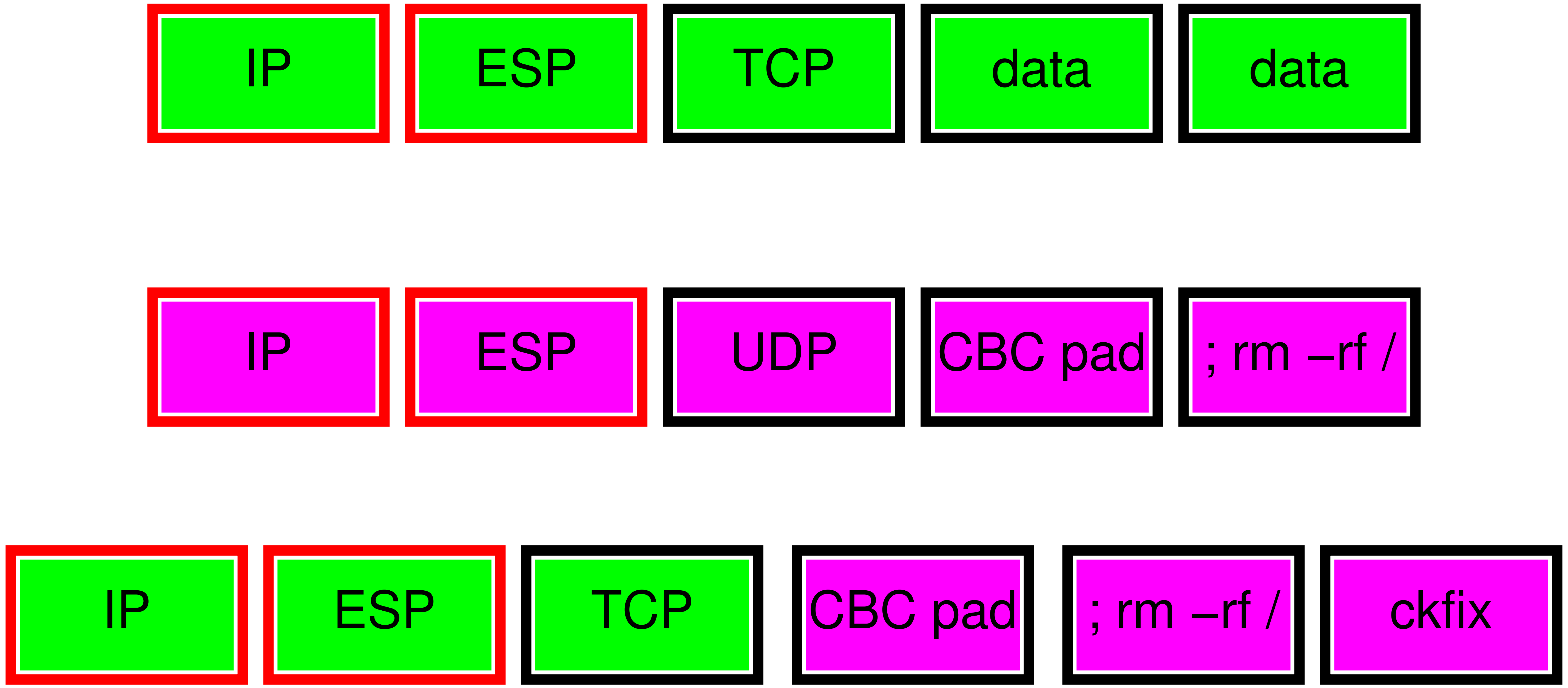
- Host-pair keying: a single key exists between each pair of hosts
- Only encryption is being done; there is no cryptographic authentication header
- The attacker may have a login on one or both of the machines
- The attacker can monitor, delete, modify, or inject messages onto the wire (a standard assumption)

Reading a Message



Paste together enemy UDP header with target's payload—
and IPsec will do the decryption for the attacker

Hijacking a Session



Use the target's TCP header, plus attack text encrypted for the enemy. Calculating a checksum fix-up isn't hard, and is only 2^{16} tries anyway

More Attacks Like These!

- Generate full-scale packets
- Guess at passwords *without* a login on either machine
- Many more!

What Went Wrong?

- We really needed sequence numbers
  - Benign packet duplication is *not* the same as malicious retransmission
- We really needed integrity checking: CBC's easy cut-and-paste properties make it crucial
- And the NSA/CBC rumor? Probably, it was the IV algorithm: *predictable* IVs are a serious weakness
- Crypto theory people had tried to tell us these things—but they weren't as engaged with the working group: the in-person standards process still matters

Fixing IPsec

- The old ESP spec was discarded
- The new one has a sequence number field and an integrity field
  - Yes—I argued to take out sequence numbers, and then argued to put them back in…
  - Integrity can *still* be turned off—again, for high speed, bulk transmissions

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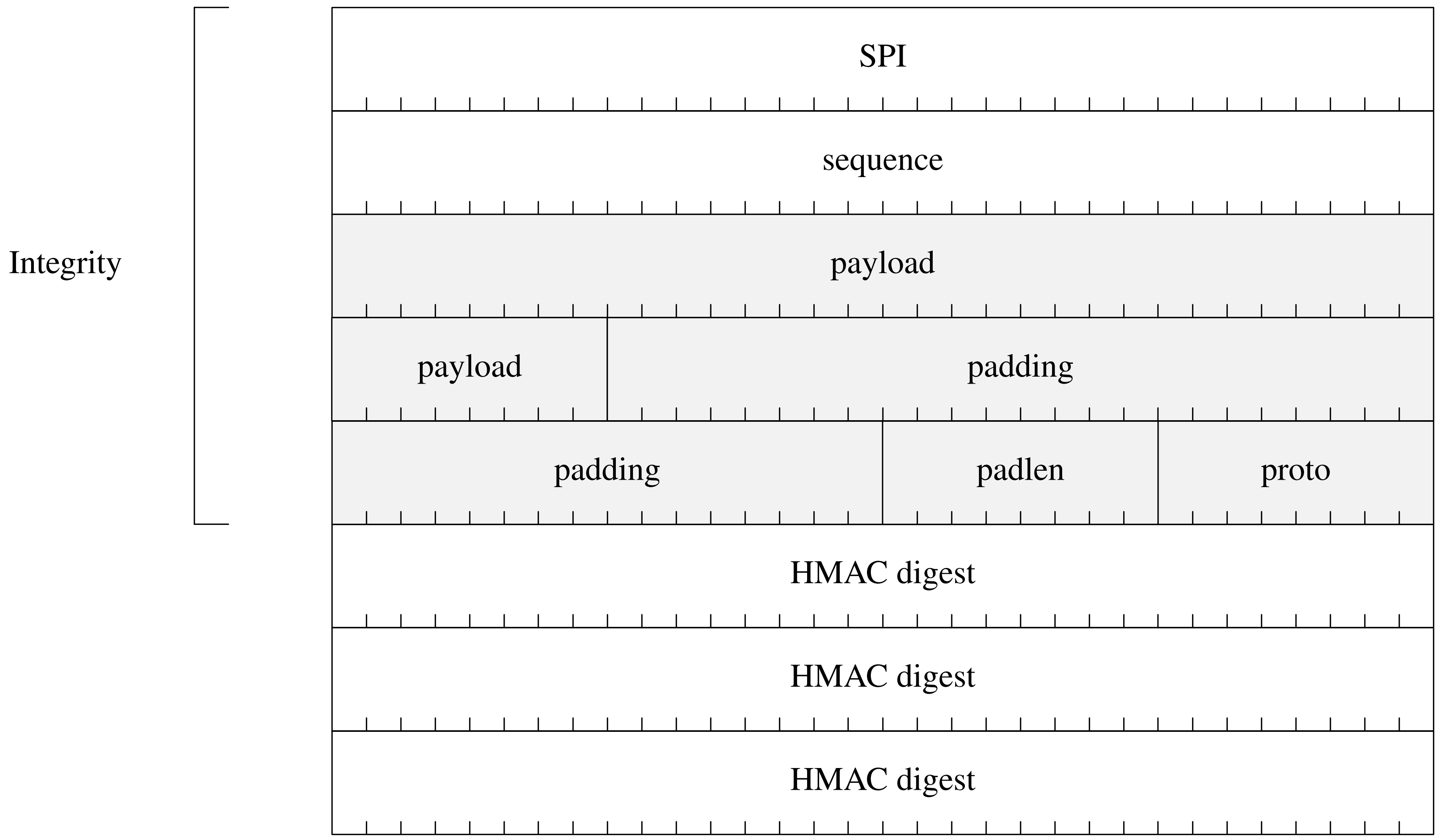
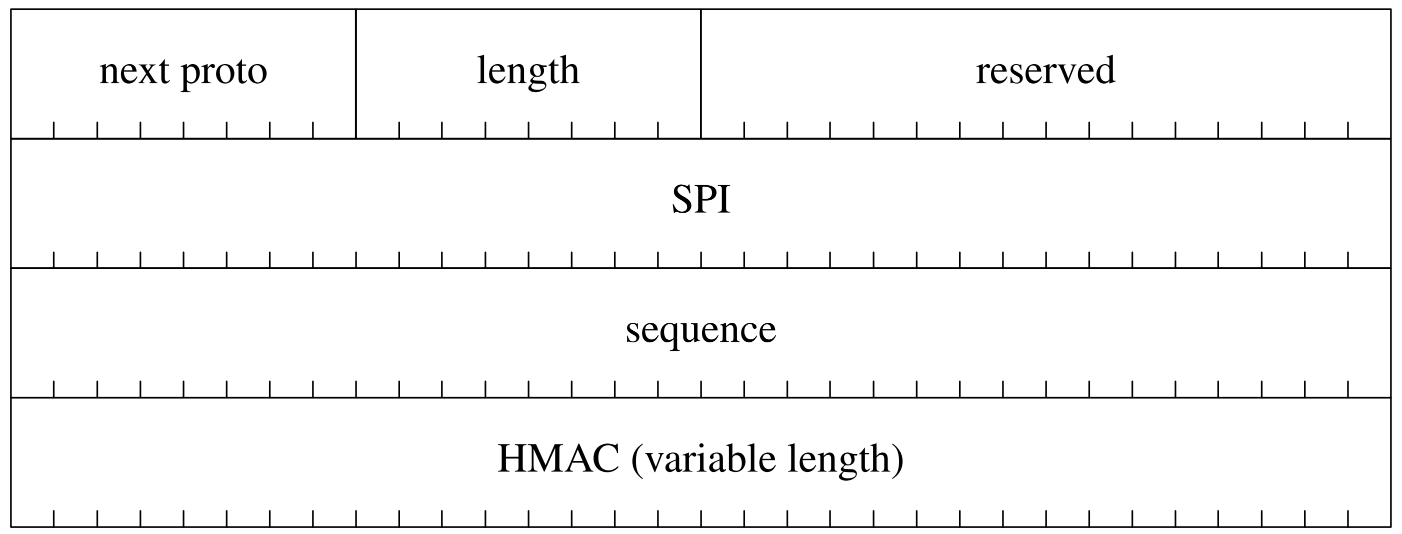
New ESP and AH Formats





AH Isn’t Needed

- Don’t need to protect IP addresses; they’re bound to the SPI
- Can’t protect other interesting IP header fields, e.g., source routing, since they change en route
- Use a “null cipher” option for authentication-only with ESP
- Many in the IETF would like to move away from it

Many Sequence Numbers?

- The IP, TCP, and ESP headers all have sequence numbers—are they redundant?
- No—they serve different purposes
- From a security perspective, the ESP sequence numbers are *within the cryptographic module's trust boundary*. TCP's are not.
- Module boundaries matters—and for security stuff, you want to trust as little as possible from outside

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Key Management

- Because of the complexity and bugs of ISAKMP/IKE, the IETF adopted a newer, (somewhat) simpler version
- Many people were still unhappy
  - Some of us proposed a replacement for IKE, JFK (“Just Fast Keying”)
  - The IETF adopted it—and at the next meeting, changed its mind and went back to the replacement IKE

Other Changes

- Newer cryptographic algorithms and modes of operation have been adopted
  - Elliptic curve, AES, combined confidentiality/integrity cipher modes, longer keys, etc.
- IKE had another, unforeseen bug: new hash algorithms couldn't be negotiated properly
- The sequence number field was too small: 32 bits

Feature Summary

	SP3	swIPe	SKIP	Original IPsec	Final IPsec
Integrity	Optional; linked to KEY_ID	Optional; flag in header	Optional; flag in header	Optional; requires AH header	Encouraged; linked to SPI
Algorithms	Linked to KEY_ID	Linked to key identifier	Given in header	Linked to SPI	Linked to SPI
Sequence Numbers	No	Yes	Optional; flag in header	No	Yes
Inner Header	Sometimes present; it's complicated	Always	Optional; flag in header	Optional; flag in header	Optional; flag in header

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Lessons

- Real-world cryptographic protocols have to be *engineered*—the cryptographic mathematics alone do not suffice
- People matter—we didn't always have (or heed) the proper expertise
- Process matters
- Requirements vary over time, as speeds increase, threats change, and newer algorithms are developed

Did We Succeed?

- ESP and AH are pretty clean
  - But it was hard for applications to tell if or how a connection was protected, especially since IPsec could be outboard
  - The IETF doesn't do APIs
- ISAKMP/IKE was (is) a disaster—far too many options made configuration and interoperability very, very difficult
- The ubiquity of the Web and the spread of SSL (aka TLS) made IPsec less interesting
- Other technologies, especially NATs and firewalls, got in the way of IPsec
- Username selectors were a bad idea—wrong layer
- **We did not get ubiquitous network-layer crypto, but we did get VPNs**

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Questions?

Brown creeper, Central Park, April 2, 2019

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