Part 3

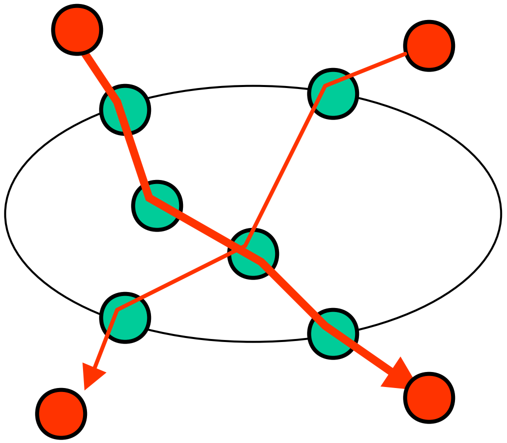
Measurements and Models for Traffic Engineering

Traffic Engineering

- Goal: domain-wide control & management to
  - Satisfy performance goals
  - Use resources efficiently
- Knobs:
  - Configuration & topology: provisioning, capacity planning
  - Routing: OSPF weights, MPLS tunnels, BGP policies,...
  - Traffic classification (diffserv), admission control,...
- Measurements are key: closed control loop
  - Understand current state, load, and traffic flow
  - Ask what-if questions to decide on control actions
  - Inherently coarse-grained

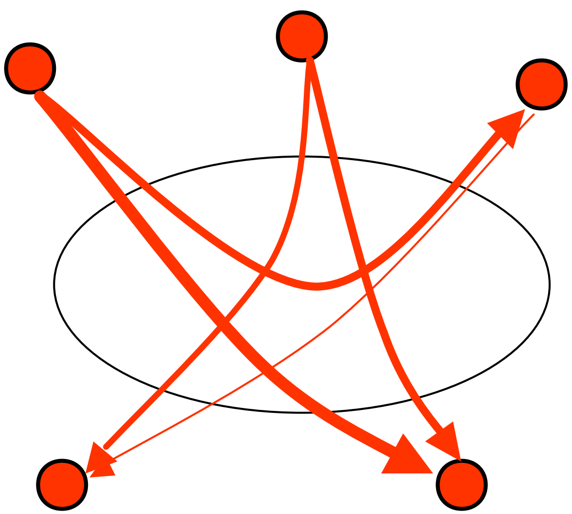
End-to-End Traffic & Demand Models

Ideally, captures
all the information about
the current network **state**
and behavior



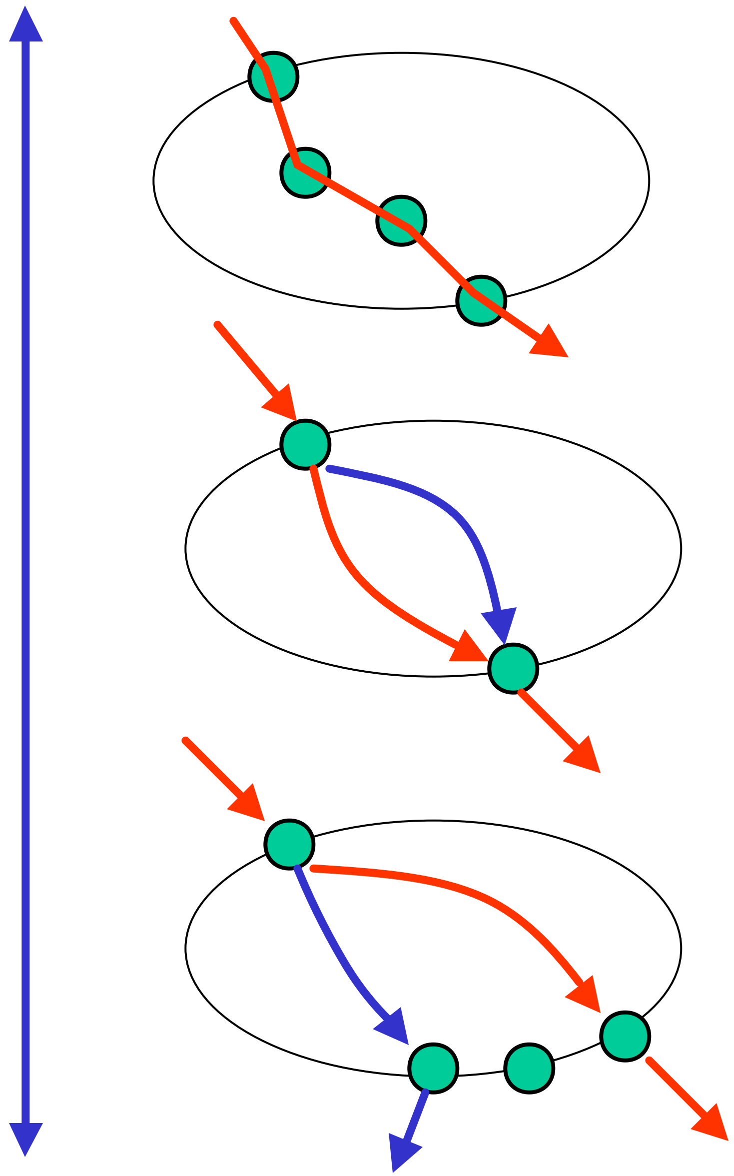
path matrix =
bytes per path

Ideally, captures
all the information that is
invariant with respect to
the network state



demand matrix =
bytes per source-
destination pair

Domain-Wide Traffic & Demand Models



current state & traffic flow

fine grained: path matrix = bytes per path

predicted control action: impact of intra-domain routing

intradomain focus: traffic matrix = bytes per ingress-egress

predicted control action: impact of inter-domain routing

interdomain focus: demand matrix = bytes per ingress and set of possible egresses

Traffic Representations

- Network-wide views
  - Not directly supported by IP (stateless, decentralized)
  - Combining elementary measurements: traffic, topology, state, performance
  - Other dimensions: time & time-scale, traffic class, source or destination prefix, TCP port number
- Challenges
  - Volume
  - Lost & faulty measurements
  - Incompatibilities across types of measurements, vendors
  - Timing inconsistencies
- Goal
  - Illustrate how to populate these models: data analysis and inference
  - Discuss recent proposals for new types of measurements

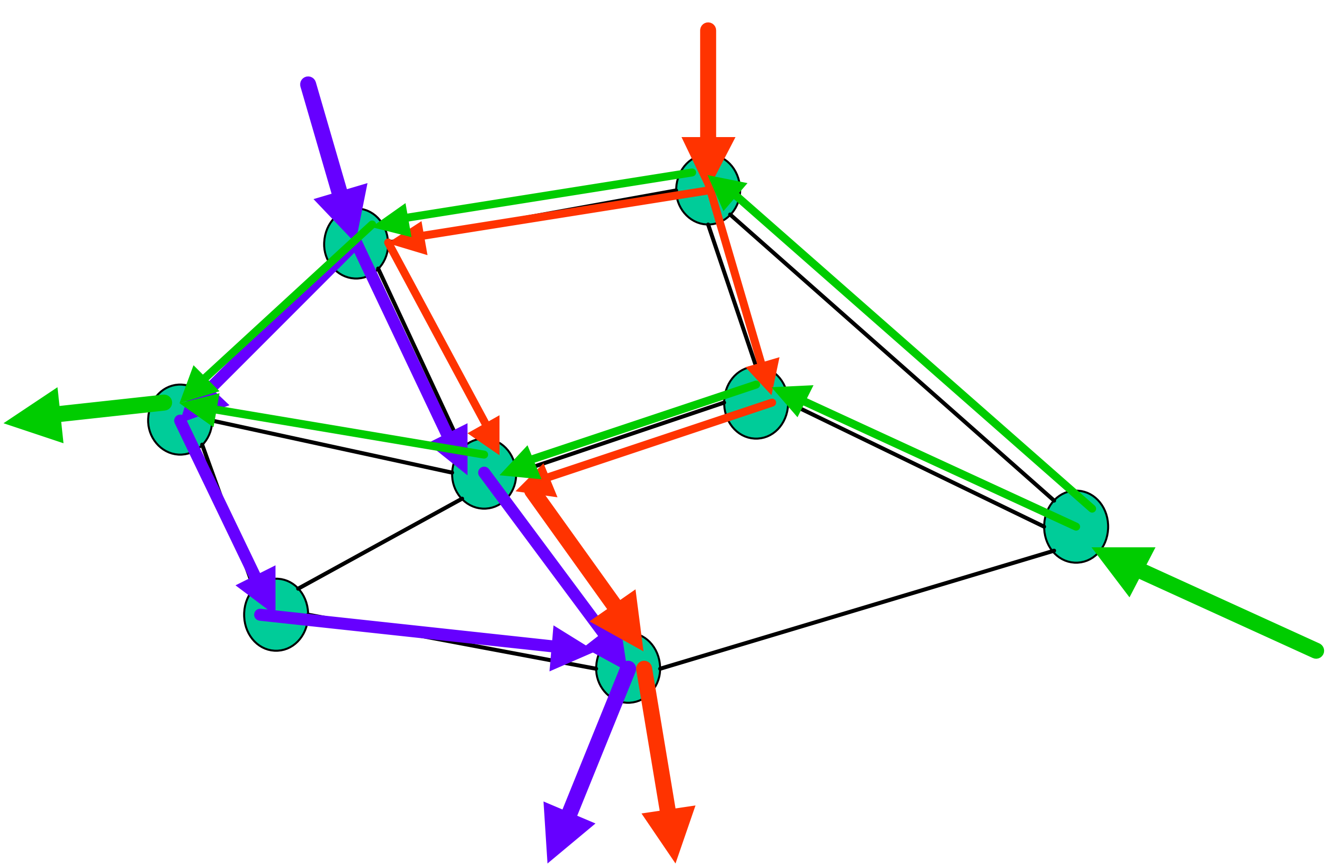
Outline

- Path matrix
  - Trajectory sampling
  - IP traceback
- Traffic matrix
  - Network tomography
- Demand matrix
  - Combining flow and routing data

Path Matrix: Operational Uses

- Congested link
  - Problem: easy to detect, hard to diagnose
  - Which traffic is responsible?
  - Which customers are affected?
- Customer complaint
  - Problem: customer has insufficient visibility to diagnose
  - How is the traffic of a given customer routed?
  - Where does it experience loss & delay?
- Denial-of-service attack
  - Problem: spoofed source address, distributed attack
  - Where is it coming from?

Path Matrix



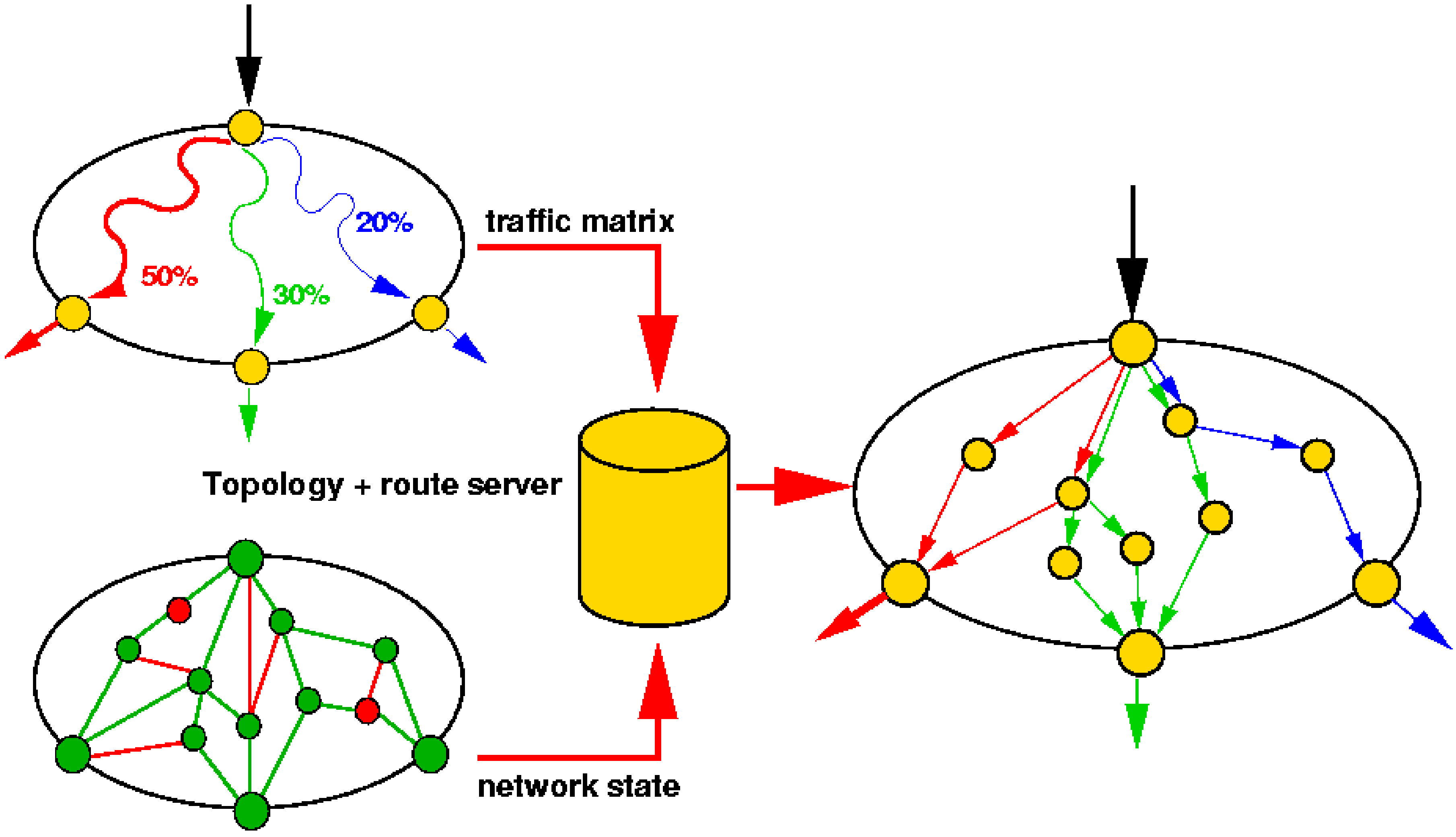
- Bytes/sec for every path P between every ingress-egress pair
- Path matrix ⇒traffic matrix

Measuring the Path Matrix

- Path marking
  - Packets carry the path they have traversed
  - Drawback: excessive overhead
- Packet or flow measurement on every link
  - Combine records to obtain paths
  - Drawback: excessive overhead, difficulties in matching up flows
- Combining packet/flow measurements with network state
  - Measurements over cut set (e.g., all ingress routers)
  - Dump network state
  - Map measurements onto current topology

Path Matrix through Indirect Measurement

- Ingress measurements + network state



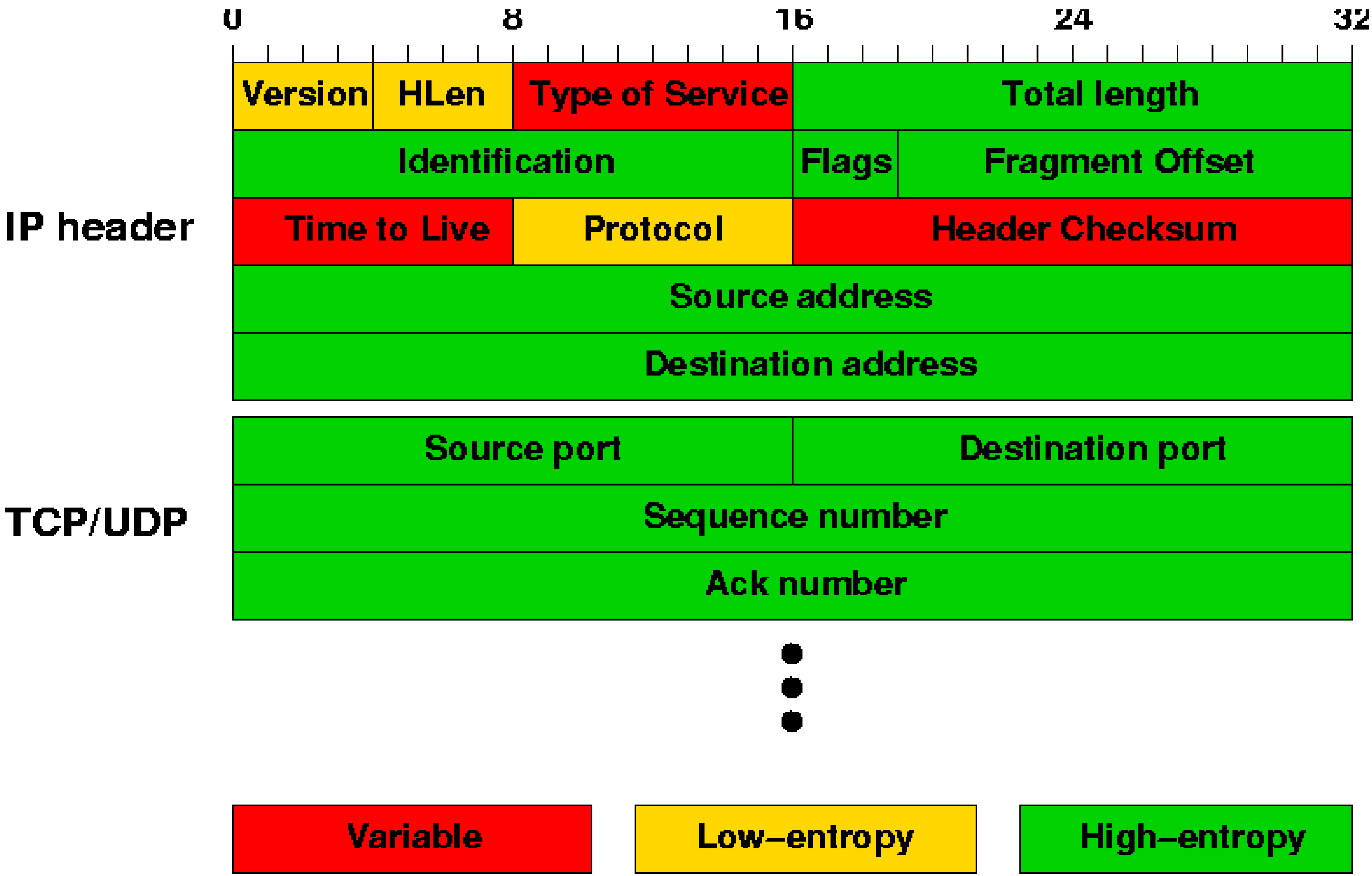
Network State Uncertainty

- Hard to get an up-to-date snapshot of...
- ...routing
  - Large state space
  - Vendor-specific implementation
  - Deliberate randomness
  - Multicast
- ...element states
  - Links, cards, protocols,...
  - Difficult to infer
- ...element performance
  - Packet loss, delay at links

Trajectory Sampling

- Goal: direct observation
  - No network model & state estimation
- Basic idea #1:
  - Sample packets at each link
  - Would like to either sample a packet *everywhere* or *nowhere*
  - Cannot carry a « sample/don't sample » flag with the packet
  - Sampling decision based on hash over packet content
  - Consistent sampling $\Rightarrow$ trajectories
    - x: subset of packet bits, represented as binary number
    - h(x) = x mod A
    - sample if h(x) < r
    - r/A: thinning factor
- Exploit entropy in packet content to obtain statistically representative set of trajectories

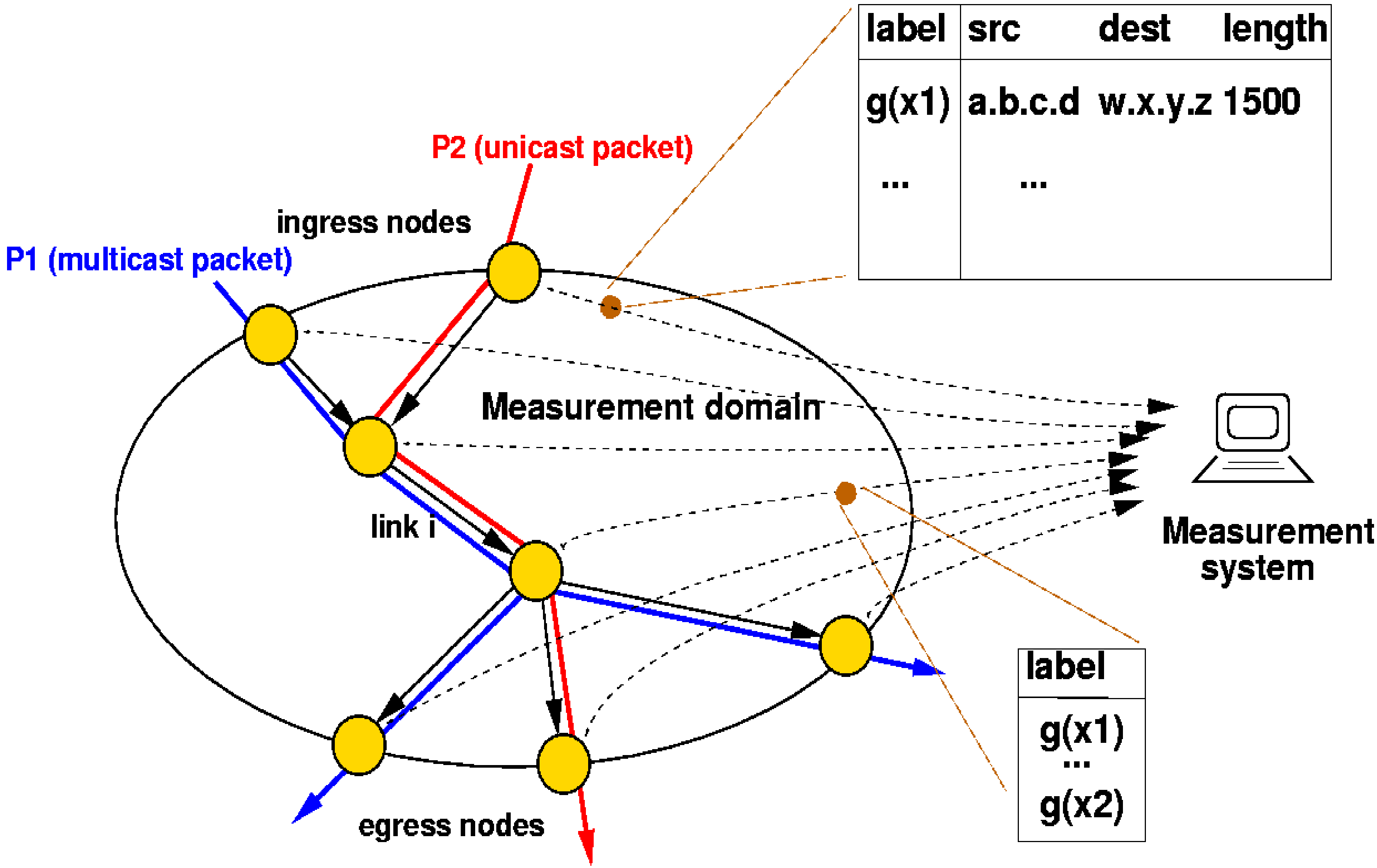
Fields Included in Hashes



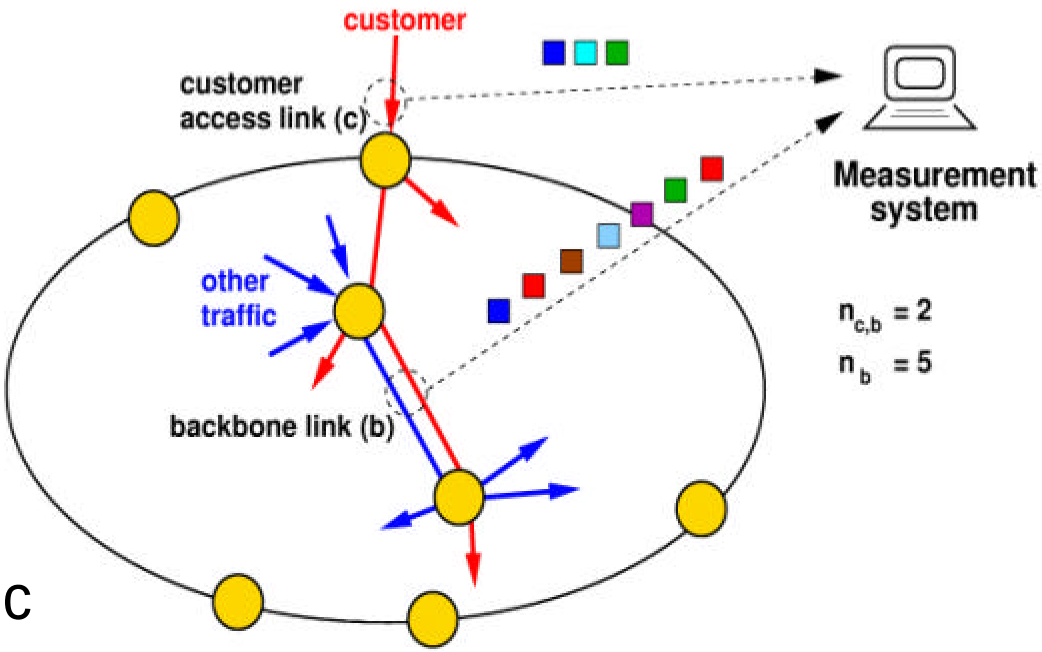
Labeling

- Basic idea #2:
  - Do not need entire packet to reconstruct trajectory
  - Packet identifier: computed through second hash function g(x)
  - Observation: small labels (20-30 bits) are sufficient to avoid collisions

Sampling and Labeling



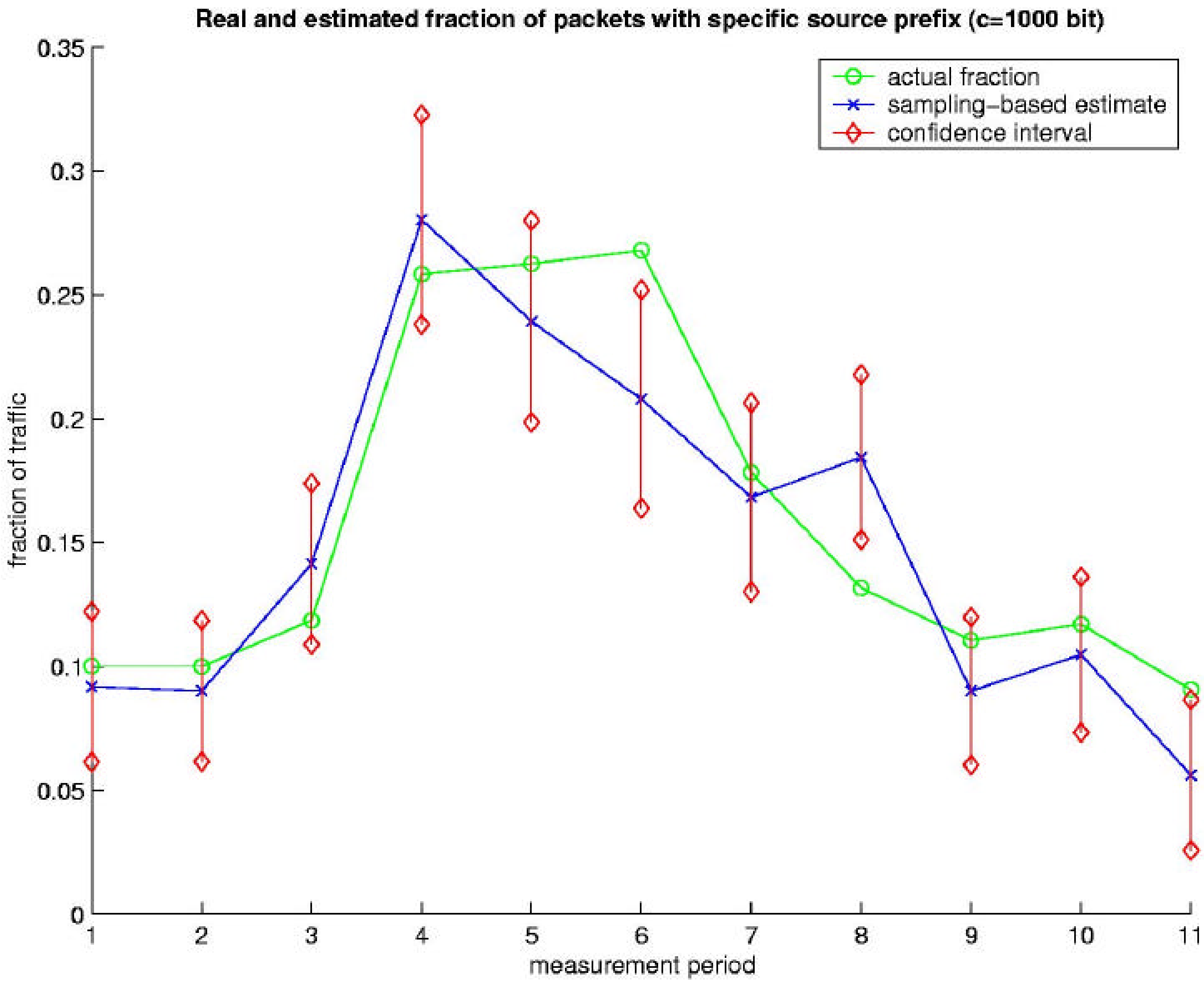
Inference Experiment



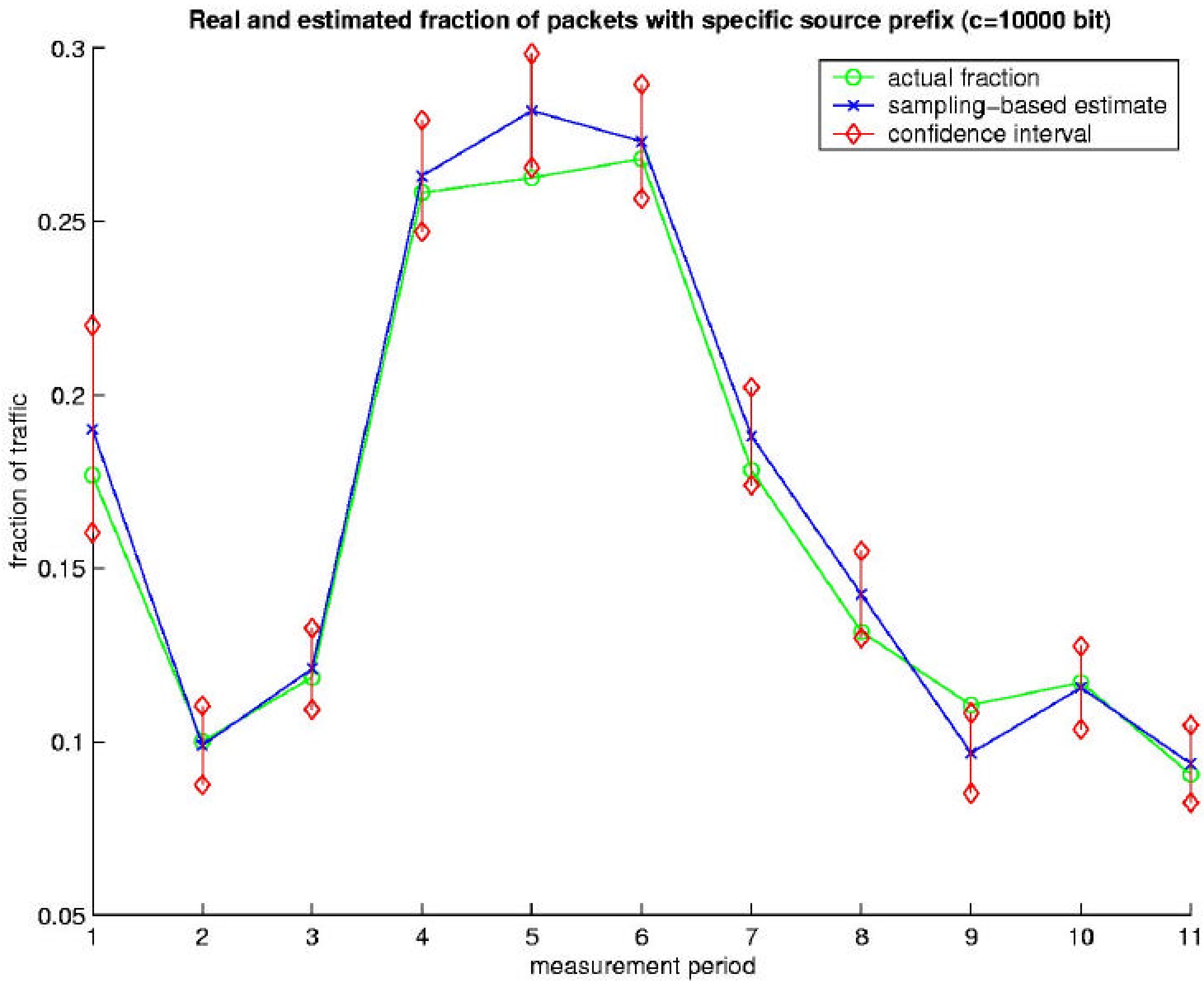
- Experiment:
  infer from trajectory samples
  - Estimate fraction of traffic from customer
  - Source address -> customer
  - Source address -> sampling + label
- Fraction of customer traffic on backbone link: $\hat{m}$

$$\hat{m} = \frac{\#\ \text{unique labels common on b, c}}{\#\ \text{unique labels on b}}$$

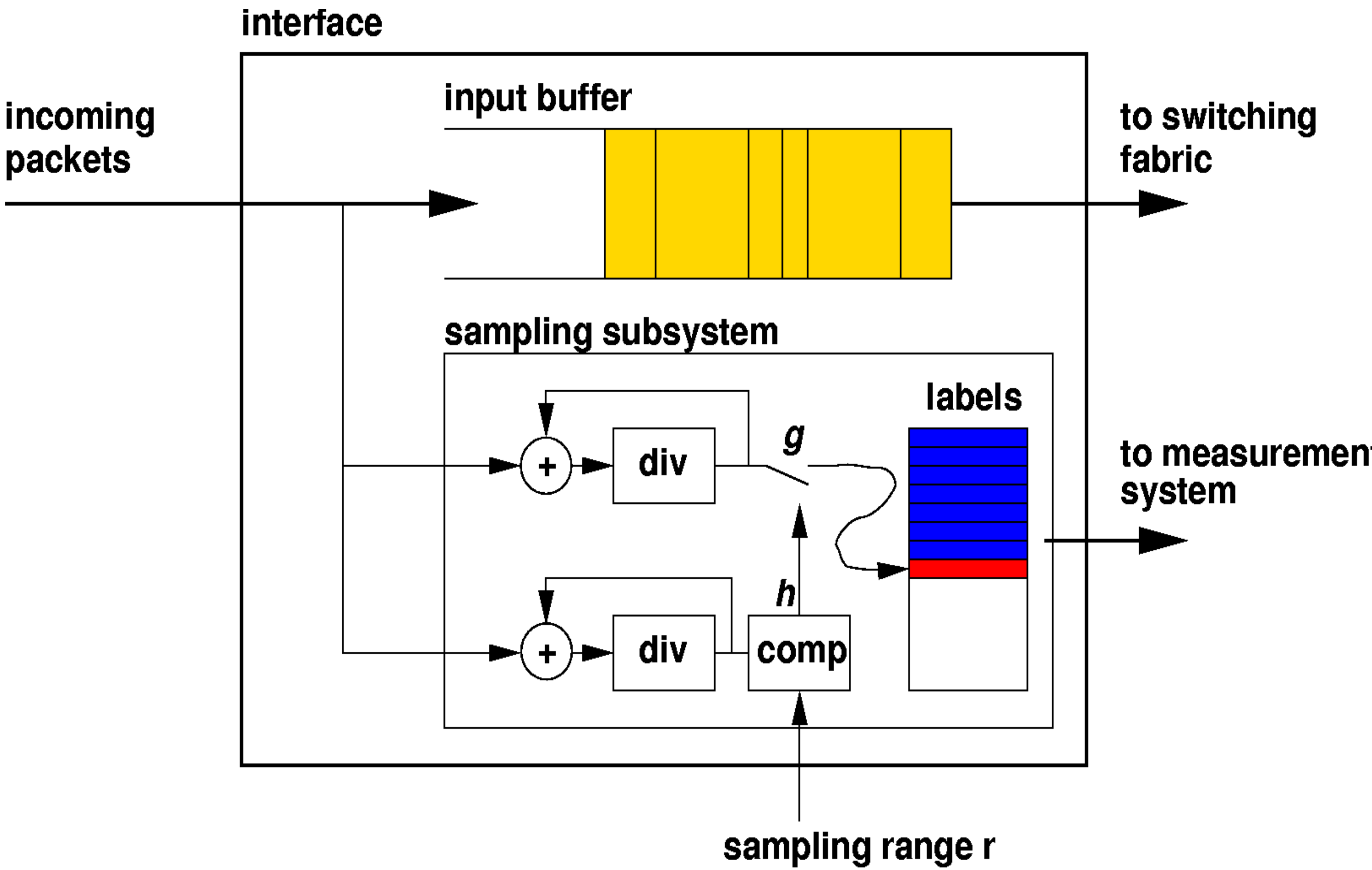
Estimated Fraction (c=1000bit)



Estimated Fraction (c=10kbit)



Sampling Device

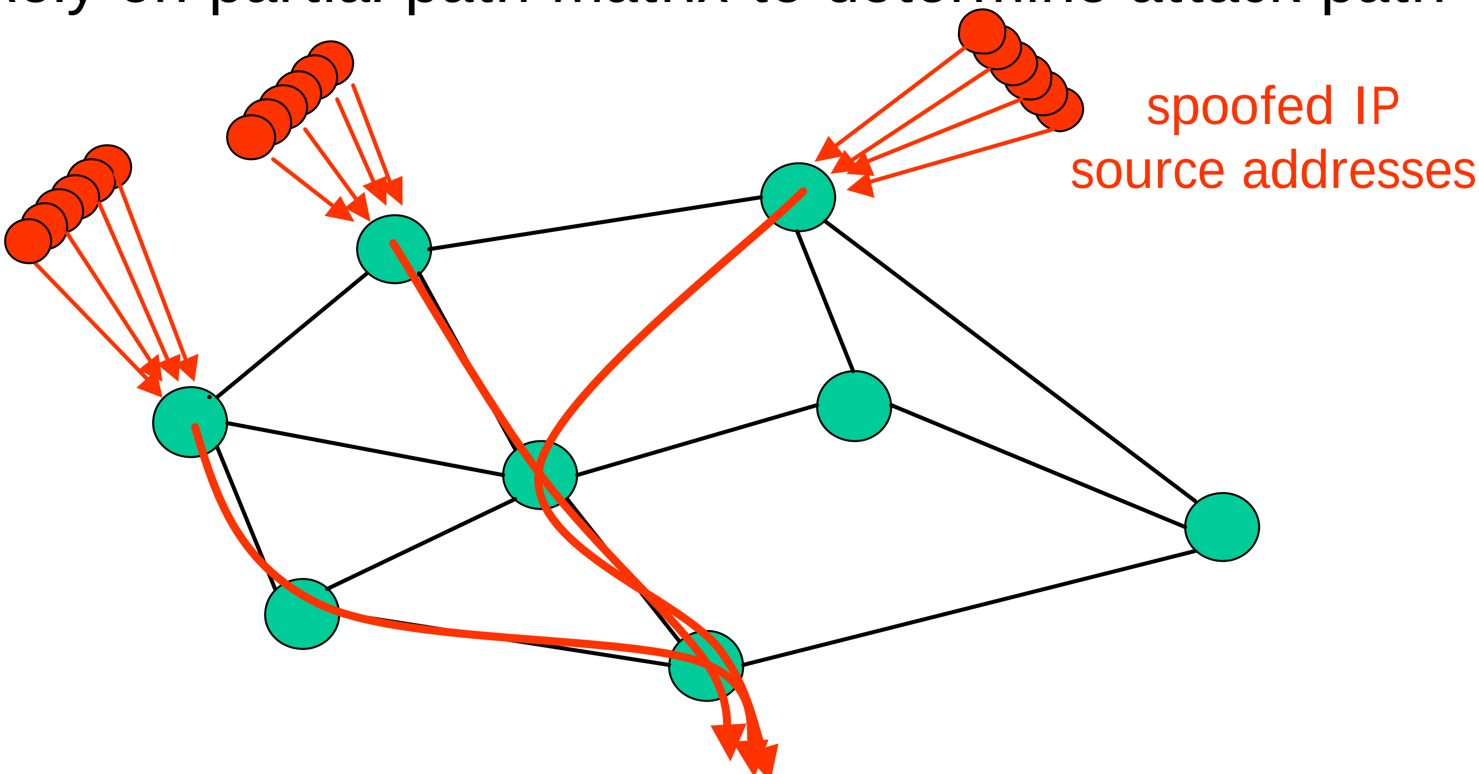


Trajectory Sampling: Summary

- Advantages
  - Trajectory sampling estimates path matrix ...and other metrics: loss, link delay
  - Direct observation: no routing model + network state estimation
  - Can handle multicast traffic (source tree), spoofed source addresses (denial-of-service attacks)
  - Control over measurement overhead
- Disadvantages
  - Requires support on linecards

IP Traceback against DDoS Attacks

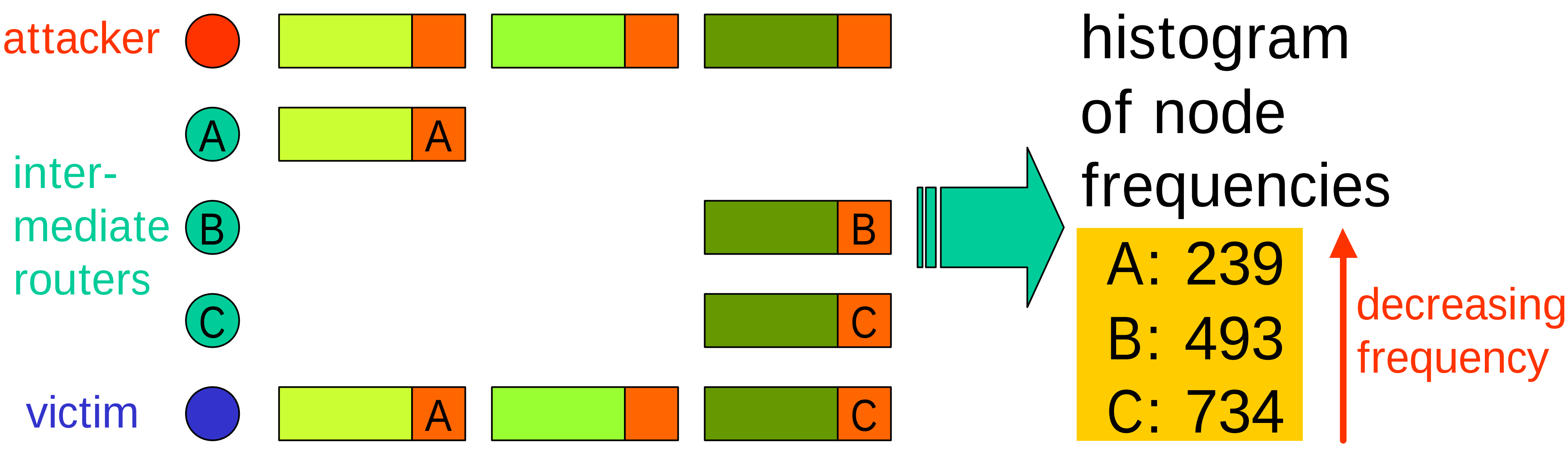
- Denial-of-service attacks
  - Overload victim with bogus traffic
  - Distributed DoS: attack traffic from large # of sources
  - Source addresses spoofed to evade detection $\rightarrow$ cannot use traceroute, nslookup, etc.
  - Rely on partial path matrix to determine attack path



IP Traceback: General Idea

- Goal:
  - Find where traffic is really originating, despite spoofed source addresses
  - Interdomain, end-to-end: victim can infer entire tree
- Crude solution
  - Intermediate routers attach their addresses to packets
  - Infer entire sink tree from attacking sources
  - Impractical:
    - routers need to touch all the packets
    - traffic overhead
- IP Traceback: reconstruct tree from samples of intermediate routers
  - A packet samples intermediate nodes
  - Victim reconstructs attack path(s) from multiple samples

IP Traceback: Node Sampling



- Router address field reserved in packet
  - Each intermediate router flips coin & records its address in field with probability p
- Problems:
  - p<0.5: spoofed router field by attacker $\rightarrow$ wrong path
  - p>0.5: hard to infer long paths
  - Cannot handle multiple attackers

IP Traceback: Edge Sampling

- Sample edges instead of nodes
  - Path is explicit $\rightarrow$ cannot introduce virtual nodes
  - Able to distinguish multiple attack paths

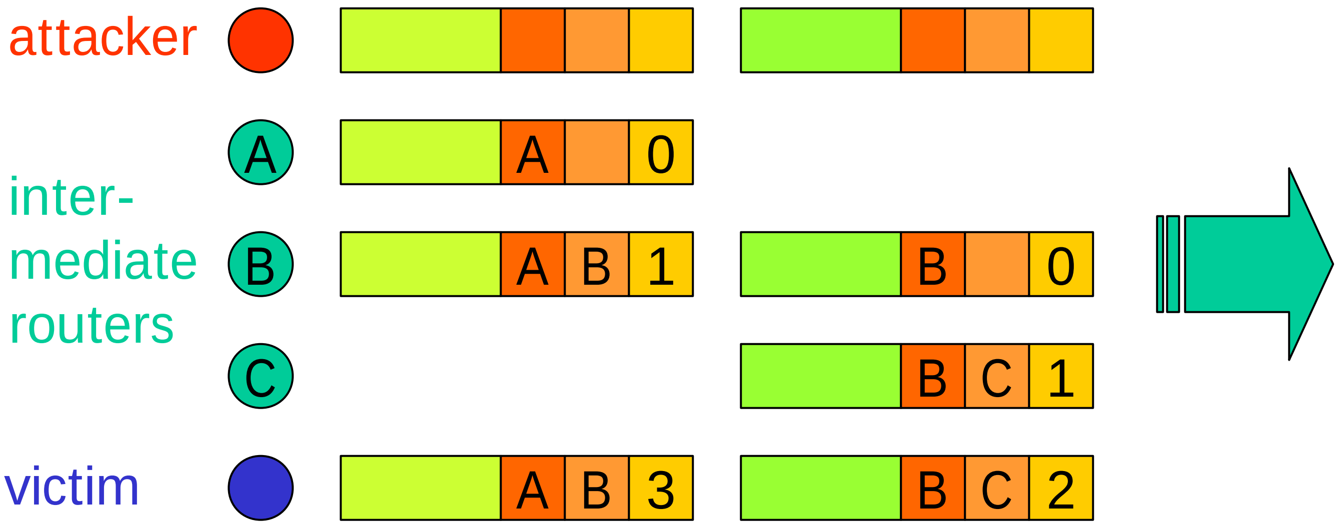


table of distances and edges

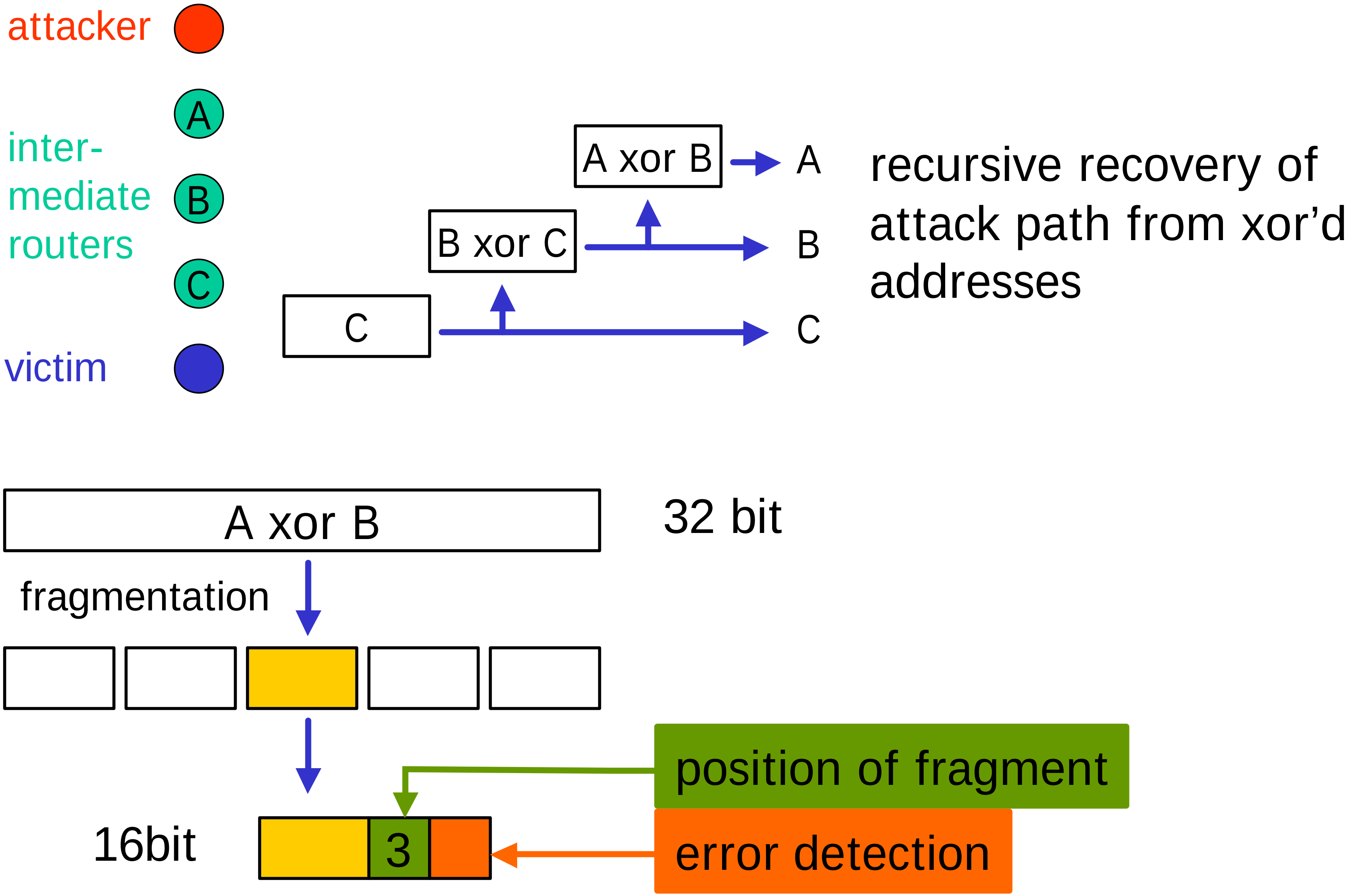
1: C$\rightarrow$victim
2: B$\rightarrow$C
3: A$\rightarrow$B
...

- Implementation
  - 3 fields: edge_start, edge_end, dist
  - With probability p: edge_start:=router, dist:=0, else dist++
  - If node receives packet with dist=0, writes its address into edge_end

IP Traceback: Compressed Edge Sampling

- Avoid modifying packet header
  - Identification field: only used for fragmentation
  - Overload to contain compressed edge samples
- Three key ideas:
  - Both_edges := edge_start `xor` edge_end
  - Fragment both_edges into small pieces
  - Checksum to avoid combining wrong pieces

Compressing Edge Sampling into ID Field



IP Traceback: Summary

- Interdomain and end-to-end
  - Victim can infer attack sink tree from sampled topology information contained in packets
  - Elegantly exploits basic property of DoS attack: large # of samples
- Limitations
  - ISPs implicitly reveal topology
  - Overloading the id field: makes fragmentation impossible, precludes other uses of id field
    - other proposed approach uses out-of-band ICMP packets to transport samples
- Related approach: hash-based IP traceback
  - "distributed trajectory sampling", where trajectory reconstruction occurs on demand from local information

Path Matrix: Summary

- Changing routers vs. changing IP
  - Both trajectory sampling and IP traceback require router support
  - This is hard, but easier than changing IP!
  - If IP could be changed:
    - trajectory sampling: sample-this-packet bit, coin flip at ingress
    - IP traceback: reserved field for router sampling
  - Tricks to fit into existing IP standard
    - trajectory sampling: consistent sampling by hashing over packet
    - IP traceback: edge sampling, compression, error correction
- Direct observation
  - No joining with routing information
  - No router state

Outline

- Path matrix
  - Trajectory sampling
  - IP traceback
- Traffic matrix
  - Network tomography
- Demand matrix
  - Combining flow and routing data

Traffic Matrix: Operational Uses

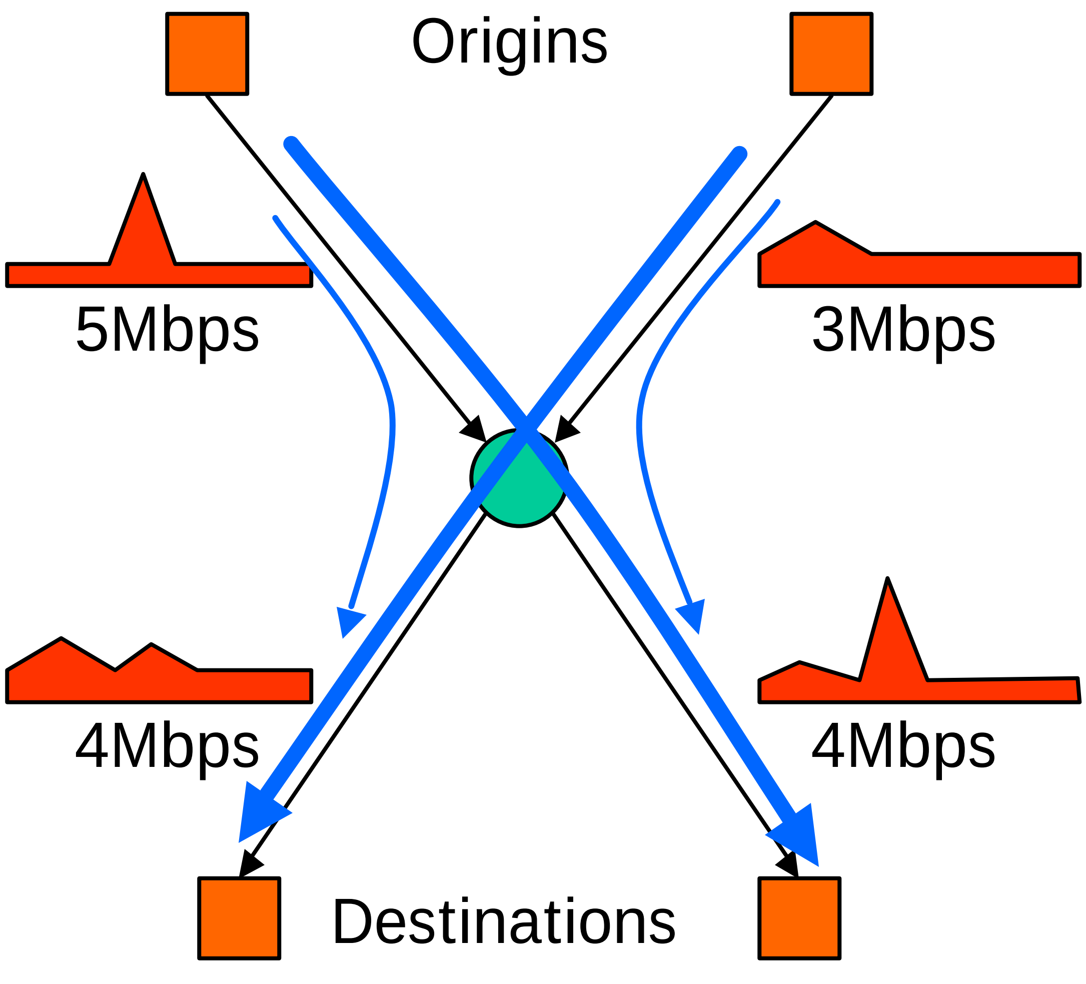
- Short-term congestion and performance problems
  - Problem: predicting link loads and performance after a routing change
  - Map traffic matrix onto new routes
- Long-term congestion and performance problems
  - Problem: predicting link loads and performance after changes in capacity and network topology
  - Map traffic matrix onto new topology
- Reliability despite equipment failures
  - Problem: allocating sufficient spare capacity after likely failure scenarios
  - Find set of link weights such that no failure scenario leads to overload (e.g., for “gold” traffic)

Obtaining the Traffic Matrix

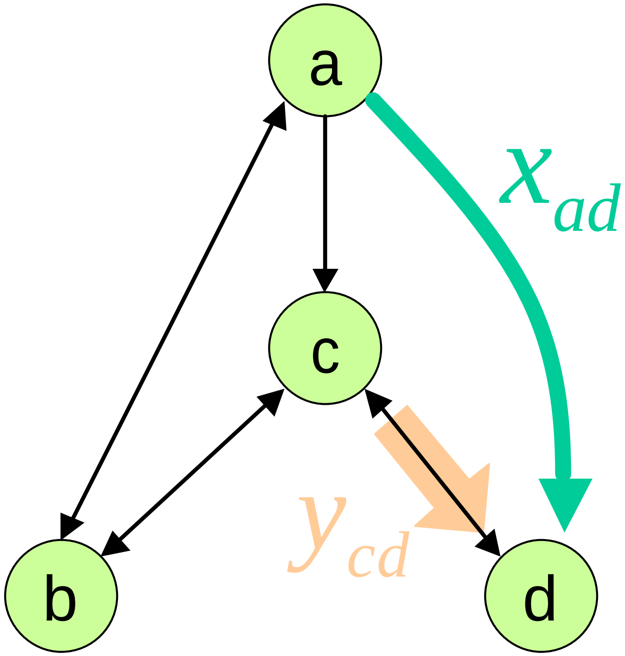
- Full MPLS mesh:
  - MPLS MIB per LSP
  - Establish a separate LSP for every ingress-egress point
- Packet monitoring/flow measurement with routing
  - Measure at ingress, infer egress (or vice versa)
  - Last section
- Tomography:
  - Assumption: routing is known (paths between ingress-egress points)
  - Input: multiple measurements of link load (e.g., from SNMP interface group)
  - Output: statistically inferred traffic matrix

Network Tomography

From link counts to the traffic matrix



Matrix Representation



$$A = \begin{bmatrix} 1 & & & & & & & & & & & \\ & 1 & 1 & & & 1 & & & & & & \\ & & & 1 & & 1 & 1 & & & 1 & & \\ & & & & 1 & & & & & & & \\ & & & & & & 1 & 1 & & 1 & 1 & \\ & & 1 & & & 1 & & & 1 & & & \\ & & & & & & & & & 1 & 1 & 1 \end{bmatrix}$$

$x = (x_1, \ldots, x_c)^T$: OD counts

$y = (y_1, \ldots, y_r)^T$: link counts

$$y = Ax$$

Single Observation is Insufficient

- Linear system is underdetermined
  - Number of links $r \approx O(n)$
  - Number of OD pairs $c \approx O(n^2)$
  - Dimension of solution sub-space at least $c - r$
- Multiple observations are needed
  - Stochastic model to bind them

Network Tomography

- [Y. Vardi, Network Tomography, JASA, March 1996]
- Inspired by road traffic networks, medical tomography
- Assumptions:
  - OD counts: $X_j^{(k)} \equiv \text{Poisson}(l_{\text{j}})$
  - OD counts independent & identically distributed (i.i.d.)
  - *K* independent observations $Y^{(1)},\ldots,Y^{(K)}$

Vardi Model: Identifiability

- Model: parameter l , observation Y
- Identifiability: $p_l(Y)$ determines l uniquely
  - Theorem: If the columns of A are all distinct and non-zero, then l is identifiable.
  - This holds for all "sensible" networks
  - Necessary is obvious, sufficient is not

Maximum Likelihood Estimator

- Likelihood function:

$$L(l) = P_l(Y) = \sum_{X:Y=AX} P_l(X)$$

- Difficulty: determining $\{X : AX = Y, X \geq 0\}$
- Maximum likelihood estimate
  - May lie on boundary of $\{X : AX = Y\}$
  - Iterative methods (such as EM) do not always converge to correct estimate

Estimator Based on Method of Moments

- Gaussian approximation of sample mean
- Match mean+covariance of model to sample mean+covariance of observation
- Mean: $Y = AX \rightarrow \hat{Y} \equiv A l$
- Cross-covariance:

$$\mathrm{cov}(Y_i, Y_j) = A \cdot \mathrm{cov}(X_i, X_j) \cdot A^T$$

$$\rightarrow \mathrm{c\hat{o}v}(Y_i, Y_j) \equiv A \cdot diag(l) \cdot A^T$$

Linear Estimation

- Linear estimating eq:

$$\begin{pmatrix} \hat{Y} \\ S \end{pmatrix} = \begin{pmatrix} A \\ B \end{pmatrix} l$$

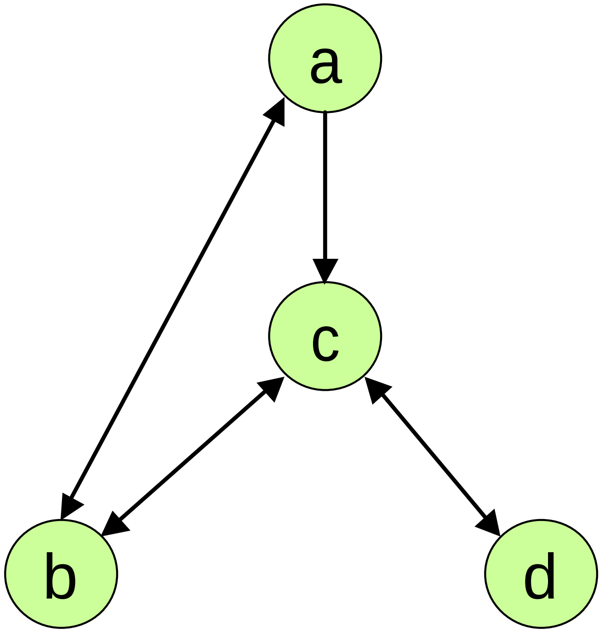
$$\hat{Y} = \frac{1}{K} \sum_{k=1}^{K} Y^{(k)} = A\,l$$

$$S_{ij} = \hat{\text{cov}}(Y_i, Y_j) = \sum_{k=1}^{K} Y_i^{(k)} Y_j^{(k)} - \hat{Y}_i \hat{Y}_j = A \cdot diag(\,l\,) \cdot A^T$$

- System inconsistent + overconstrained
  - Inconsistent: e.g., $S_{ii} \neq \hat{Y}_i^2$
  - Overconstrained: $A : r \times c; B : \frac{r(r-1)}{2} \times c$
  - Massage eqn system, LININPOS problem

How Well does it Work?

- Experiment [Vardi]:
  - K=100
- Limitations:
  - Poisson traffic
  - Small network



$$l = EX = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ 12 \end{bmatrix}, \hat{l} = \begin{bmatrix} 1.01 \\ 2.37 \\ 2.68 \\ 4.72 \\ 5.06 \\ 5.79 \\ 6.84 \\ 7.92 \\ 9.25 \\ 9.87 \\ 11.33 \\ 12.14 \end{bmatrix}$$

Further Papers on Tomography

- [J. Cao et al., Time-Varying Network Tomography, JASA, Dec 2000]
  - Gaussian traffic model, mean-variance scaling
- [Tebaldi & West, Bayesian Inference on Network Traffic..., JASA, June 1998]
  - Single observation, Bayesian prior
- [J. Cao et al., Scalable Method..., *submitted*, 2001]
  - Heuristics for efficient computation

Open Questions & Research Problems

- Precision
  - Vardi: traffic generated by model, large # of samples
  - Nevertheless significant error!
- Scalability to large networks
  - Partial queries over subgraphs
- Realistic traffic models
  - Cannot handle loss, multicast traffic
  - Marginals:Poisson & Gaussian
  - Dependence of OD traffic intensity
  - Adaptive traffic (TCP)
  - Packet loss
- How to include partial information
  - Flow measurements, packet sampling

Outline

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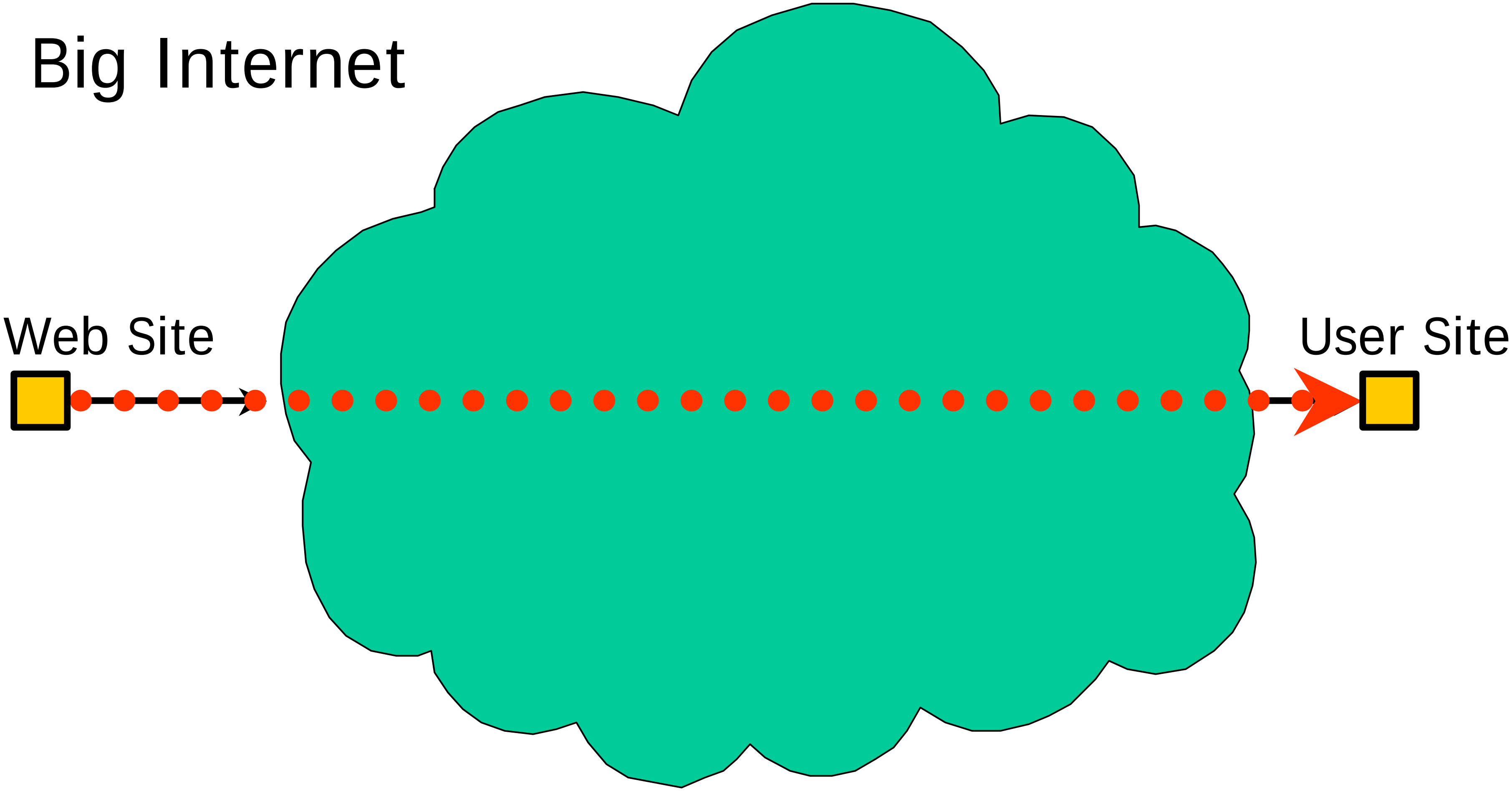
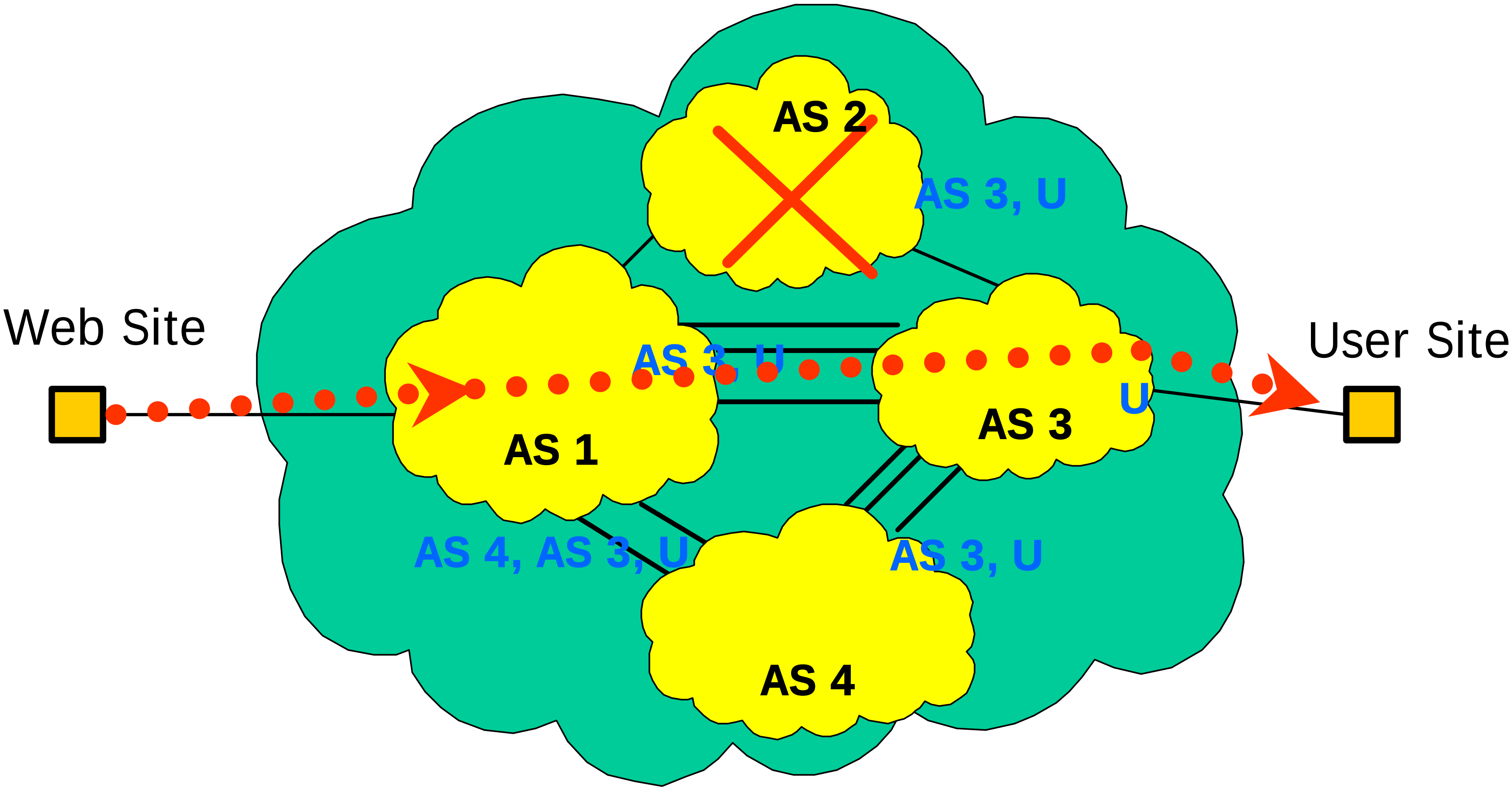
Traffic Demands



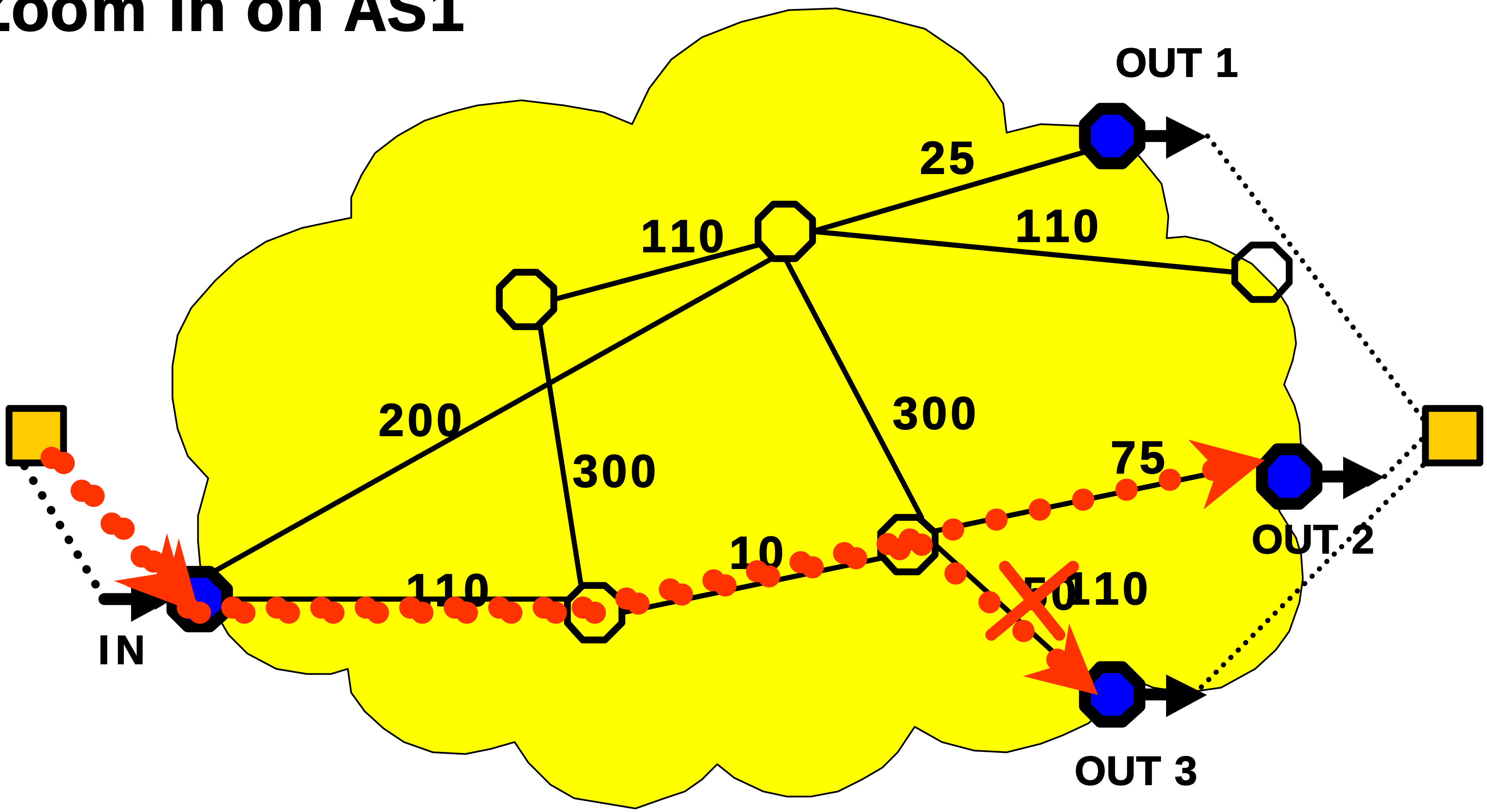
Coupling between Inter and Intradomain



- IP routing: first interdomain path (BGP), then determine intradomain path (OSPF,IS-IS)

Intradomain Routing

Zoom in on AS1



- Change in internal routing configuration changes flow exit point (hot-potato routing)

Demand Model: Operational Uses

- Coupling problem with traffic matrix-based approach:

Traffic matrix → Traffic Engineering → Improved Routing → Traffic matrix → Traffic Engineering → Improved Routing → …

  - traffic matrix changes after changing intradomain routing!

- Definition of demand matrix: # bytes for every (in, {out_1,...,out_m})
  - ingress link (in)
  - set of possible egress links ({out_1,...,out_m})

Demand matrix → Traffic Engineering → Improved Routing

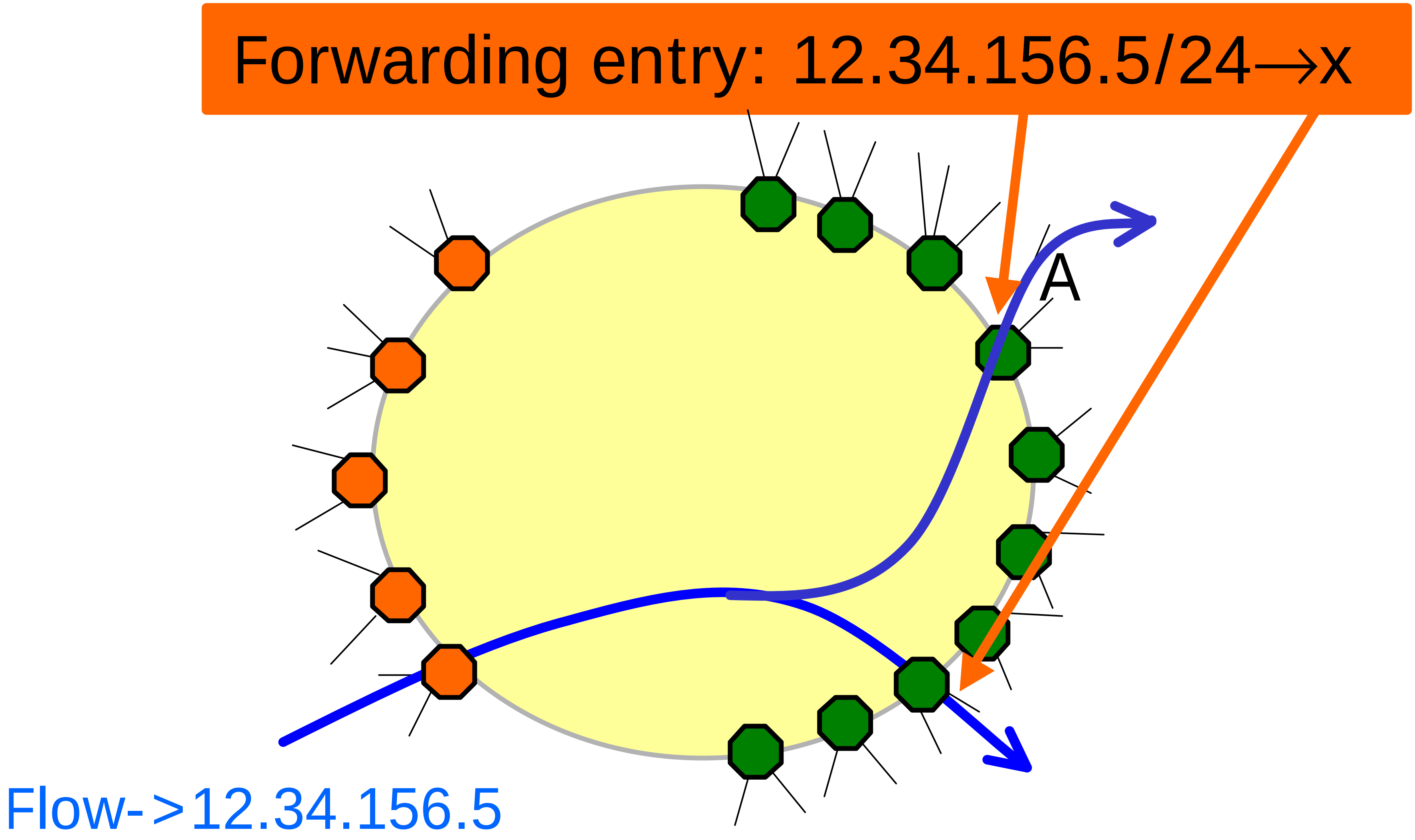
Ideal Measurement Methodology

- Measure traffic where it enters the network
  - Input link, destination address, # bytes, and time
  - Flow-level measurement (Cisco NetFlow)
- Determine where traffic can leave the network
  - Set of egress links associated with each destination address (forwarding tables)
- Compute traffic demands
  - Associate each measurement with a set of egress links

Identifying Where the Traffic Can Leave

- Traffic flows
  - Each flow has a dest IP address (e.g., 12.34.156.5)
  - Each address belongs to a prefix (e.g., 12.34.156.0/24)
- Forwarding tables
  - Each router has a table to forward a packet to “next hop”
  - Forwarding table maps a prefix to a “next hop” link
- Process
  - Dump the forwarding table from each edge router
  - Identify entries where the “next hop” is an egress link
  - Identify set of all egress links associated with a prefix

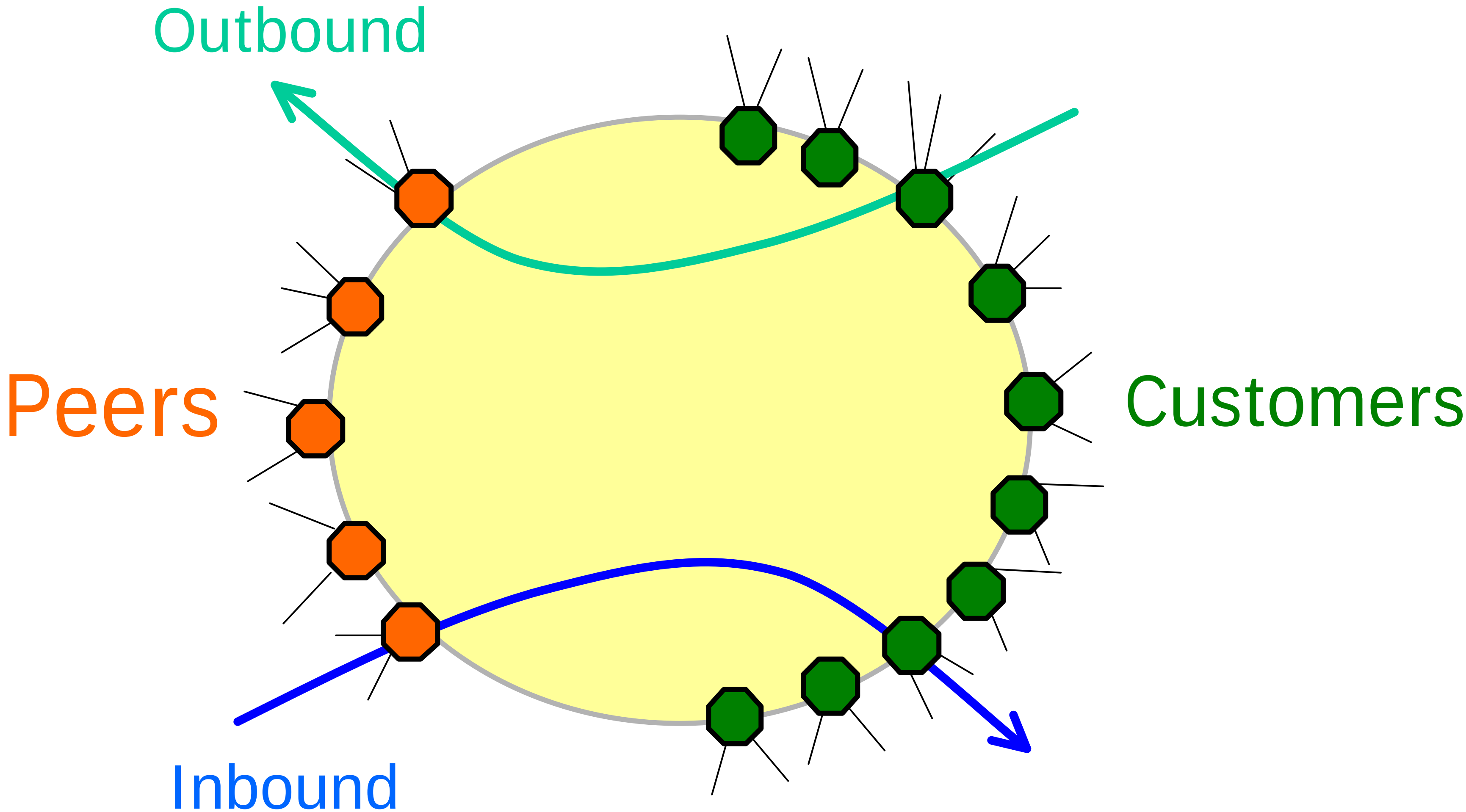
Identifying Egress Links



Case Study: Interdomain Focus

- Not all links are created equal: access vs. peering
  - Access links:
    - large number, diverse
    - frequent changes
    - burdened with other functions: access control, packet marking, SLAs and billing…
  - Peering links:
    - small number
    - stable
- Practical solution: measure at peering links only
  - Flow level measurements at peering links
    - need both directions!
  - A large fraction of the traffic is interdomain
  - Combine with reachability information from all routers

Inbound & Outbound Flows on Peering Links

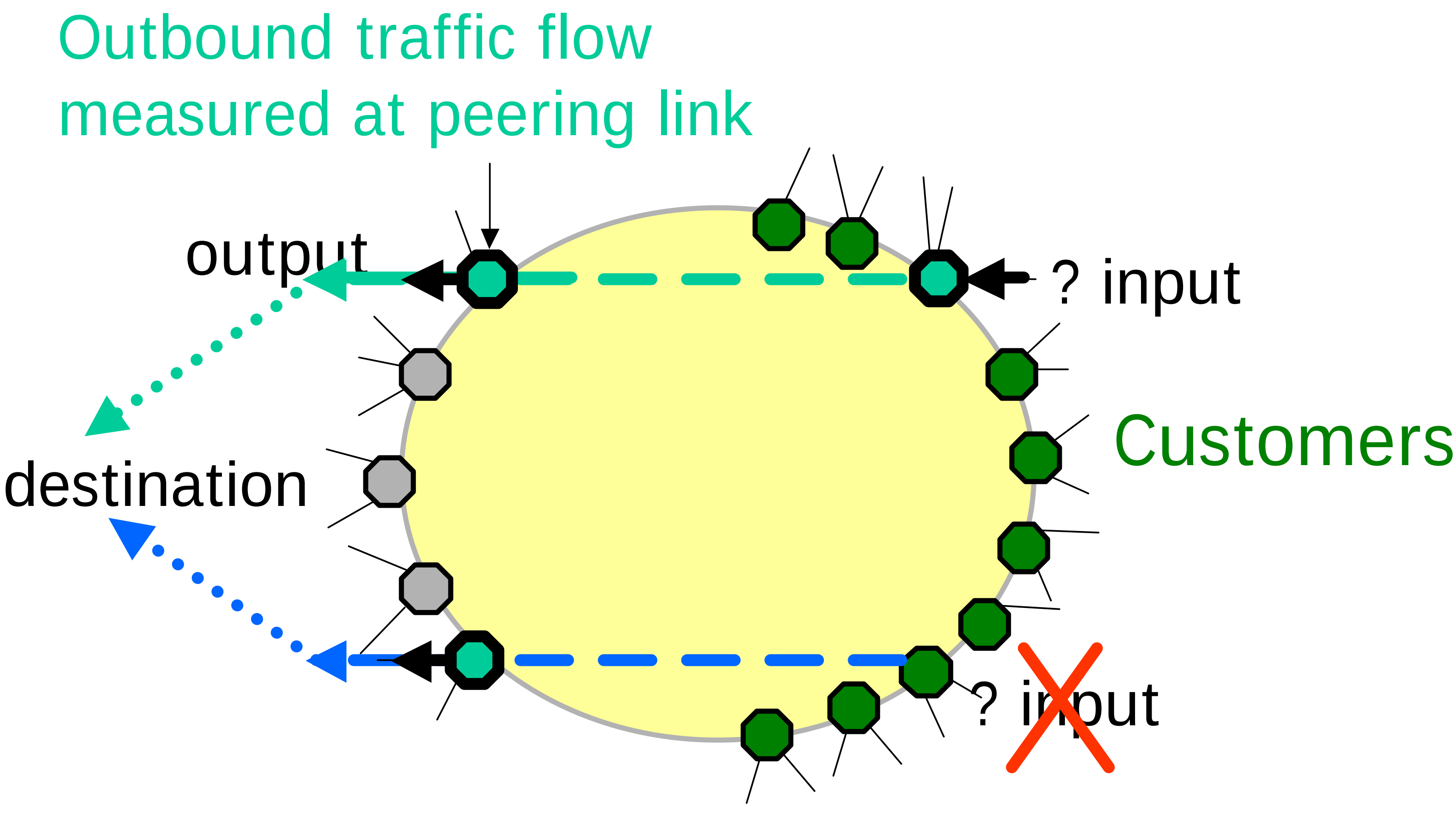


Note: Ideal methodology applies for inbound flows.

Flows Leaving at Peer Links

- Transit traffic
  - Problem: avoid double-counting
  - Either in and out at same or at different routers
  - Idea: use source address to check if flow originates at customer
    - trustworthy because of ingress filtering of customer traffic
- Outbound traffic
  - Flow measured only as it leaves the network
  - Keep flow record if source address matches a customer
  - Identify ingress link(s) that could have sent the traffic

Challenge: Ingress Links for Outbound



Use routing simulation to trace back to the ingress links -> egress links partition set of ingress links

Experience with Populating the Model

- Largely successful
  - 98% of all traffic (bytes) associated with a set of egress links
  - 95-99% of traffic consistent with an OSPF simulator
- Disambiguating outbound traffic
  - 67% of traffic associated with a single ingress link
  - 33% of traffic split across multiple ingress (typically, same city!)
- Inbound and transit traffic (uses input measurement)
  - Results are good
- Outbound traffic (uses input disambiguation)
  - Results are pretty good, for traffic engineering applications, but there are limitations
  - To improve results, may want to measure at selected or sampled customer links

Open Questions & Research Problem

- Online collection of topology, reachability, & traffic data
  - Distributed collection for scalability
- Modeling the selection of the ingress link (e.g., use of multi-exit descriminator in BGP)
  - Multipoint-to-multipoint demand model
- Tuning BGP policies to the prevailing traffic demands

Traffic Engineering: Summary

- Traffic engineering requires domain-wide measurements + models
  - Path matrix (per-path): detection, diagnosis of performance problems; denial-of-service attacks
  - Traffic matrix (point-to-point): predict impact of changes in intra-domain routing & resource allocation; what-if analysis
  - Demand matrix (point-to-multipoint): coupling between interdomain and intradomain routing: multiple potential egress points

Conclusion

- IP networks are hard to measure by design
  - Stateless and distributed
  - Multiple, competing feedback loops: users, TCP, caching, content distribution networks, adaptive routing… $\rightarrow$ difficult to predict impact of control actions
  - Measurement support often an afterthought $\rightarrow$ insufficient, immature, not standardized
- Network operations critically rely on measurements
  - Short time-scale: detect, diagnose, fix problems in configuration, state, performance
  - Long time-scale: capacity & topology planning, customer acquisition, …
- There is much left to be done!
  - Instrumentation support; systems for collection & analysis; procedures