IPV6 DIFFUSION

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Goals: Five Answers on IPv6 Diffusion

- What is a reasonable, available measure?
- Can the diffusion uncertainty be bound and quantified?
- Is there a feasible path which results is short IPv4/IPv6 co-existence?
- What observations from economics of security may apply to IPv6?
- What are the implications in terms of possible actions?

IPv6 Diffusion

- S-curve diffusion model
- Data extrapolated from ARIN
  - 60 months
- Results
  - Exhaustion of IPv4 is likely to occur before significant diffusion of IPv6

IPv6 and Economic Incentives

- Incentive alignment
- Related scholarship
  - Network effects
    - Network externalities
  - Possible Parallels
    - Patching
    - Privacy
    - Costs vs. Benefits

Network Effects

- Intrinsic and Network Benefits
  - Intrinsic
    - Derived from individual IPv6 adoption
    - Examples: No need for NATs, individually addressable devices
  - Network
    - Derived from aggregate IPv6 adoption
    - Examples: certainty of device id, enhanced security
  - Network benefits accrue to late adopters
    - Early adoption = altruism?

Patching

- Not everyone who
  - Could benefit from patching adopts
  - Could benefit from IPv6 adopts
  - How applicable are the findings?

Patching

- Findings
  - Camp: Vulnerabilities as externality
  - Ozment: Subsidies, mandates, bundling
  - Cavusoglu:
    - Lack of standardization/interoperability
    - Need for testing
    - Every network is unique
    - Concern for local idiosyncrasies

Parallels in Privacy

- Froomkin
  - Risks invisible, costs of privacy highly visible
  - IPv6: Risks invisible, costs both visible and uncertain

Parallels in Privacy

- Greenstadt et al
  - Privacy is a lemon's market
  - Merchants cannot prove privacy policy reliability
  - NSPs cannot prove value of IPv6
  - Lack of information in both cases

Parallels in Privacy

- Aquisti: Hyperbolic discounting of future risks
  - Privacy risks discounted at an ever increasing rate
  - IPv4 risks discounted
    - Exhaustion
    - Security

Costs and Benefits

- Costs are visible
  - Complex standard, potential lack of interoperability
  - Lack of maturity in technology
  - Fear of unknown
    - Routing table explosion?
    - Routing storms?
    - Total cost?
  - Tacit knowledge lost

Costs and Benefits

- Benefits invisible
  - Long-term advantage in tacit knowledge
    - For early adopters
  - Overall network benefit is security
    - Cannot be captured by early adopters
  - New commercial opportunities not quantifiable
    - Mobile
    - Ubiquitous computing

Costs

- Monetary Costs
  - Rowe estimates IPv6 adoption would cost approximately $25 billion over 25 years
- Time Costs
- Personnel Costs
- Discrepancy between costs and expected benefits burdens early adopters

Security Costs

- IPv6 may temporarily increase security vulnerabilities
  - Interoperability issues
  - Maturity of code base
  - Mis-configuration due to inexperience
- Security costs weigh heavily on early adopters

Diffusion

- Probit model
  - Firm-specific diffusion
  - Compares characteristics of early adopters, current adopters and thus implicitly, late (e.g., non-adopters)
- S-curve macroeconomic model
  - Aggregates over time
  - Implicitly integrates network effects

Probit Model

- Large dataset for econometric comparison of decision variables
  - Industry
  - Firm-specific variables
  - Firm size
  - Type
  - Organizational Structure
  - Organizational structure
  - Geography

Probit Model

- Inadequate cross-section of current adopters to perform cross-section analysis
  - IPv6 adoption dominated by .net and .gov
  - Positive
    - Most informed parties are least concerned about unknowns wrt benefits
  - Negative
    - Difficult to determine factors driving adoption
- Early in adoption cycle for effective probit analysis

S-curve Model

- Non-constant rate of adoption
  - Improvements in technology quality
  - Network effect
  - Tacit knowledge
- Different types of consumers
  - Innovators
  - Early adopters
  - Laggards
  - Refusniks

Generic Diffusion Model

$$N(t) = N(t-1)+p*N(t-1)+q*[N(t-1)]^2$$

p = innovator coefficient
q = follower coefficient

tremendous uncertainty in both

Data Analysis

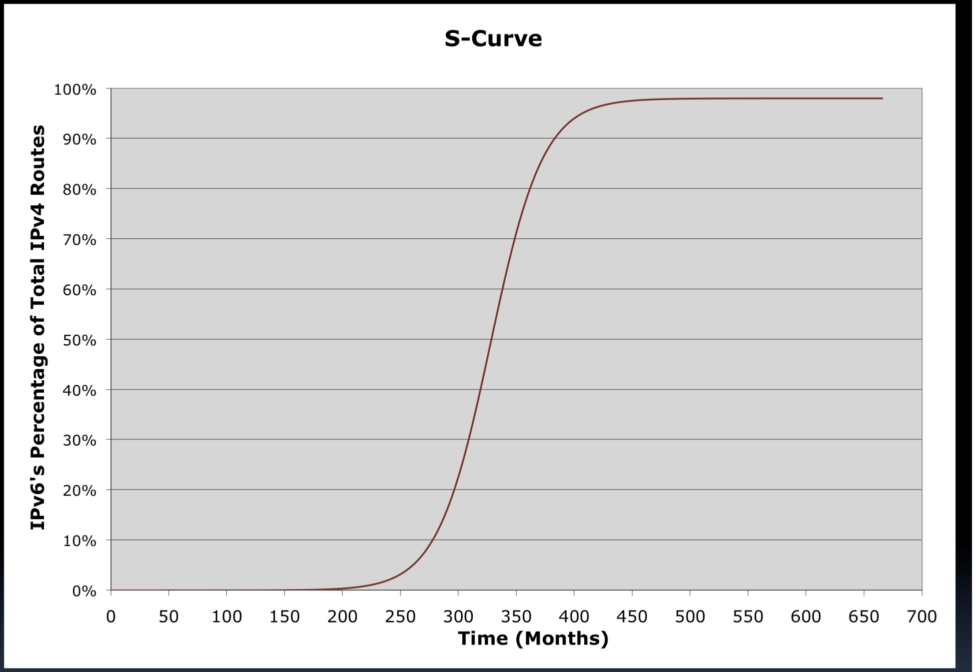
- Given current adoption rates, when might IPv6 have significant domestic market penetration?
- 3 models
  - Best-fit (most pessimistic) assumes no exogenous influence on demand for IPv6
  - Best-case assumes exogenous tipping point
  - Most optimistic given current data

Two Data Sets

- IP addresses and routes
  - Compare routes as advertised
- ASN
  - Compare Autonomous System Numbers
  - 1:1 comparison
- Cannot resolve real world uncertainty with models, but can bound uncertainty

Route Count with Standard Model: Best Fit

- Crossover point at 4% of current routes
- Occurs mid-2019

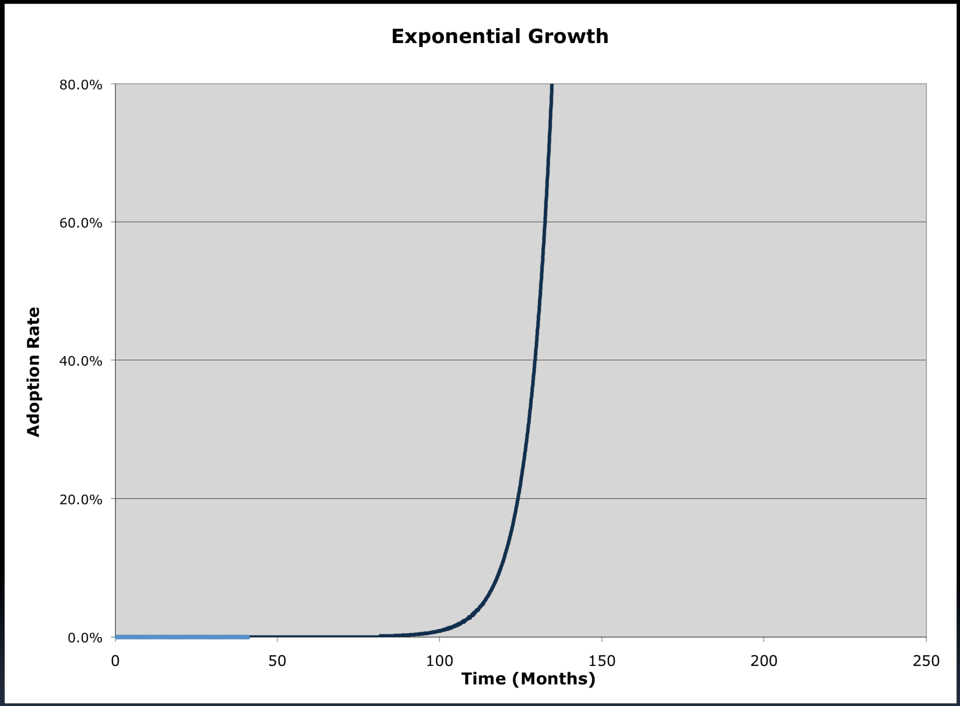


Too Little, Too Late

- At current rate of adoption, IPv6 will be 20% diffused in approximately 18 years
  - 80% diffusion in 22 years
- Analysis does not address possible exogenous forces
  - Demand push
    - e.g., IPv4 exhaustion
  - Supply pull
    - e.g., DoD commitment for suppliers

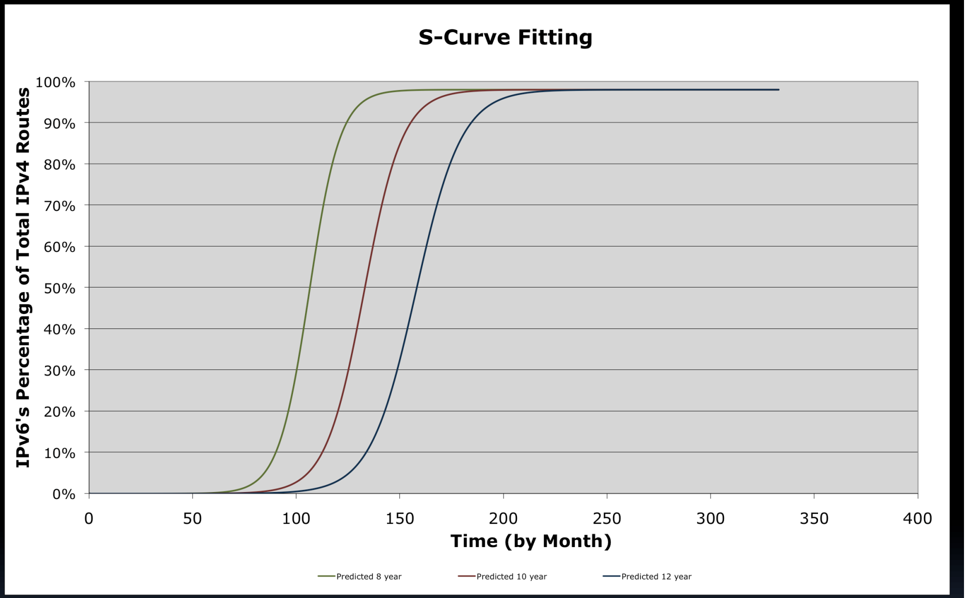
Best Case Route Count, Exponential Growth

- Assumes exponential growth in the number of IPv6 adopters
  - Exogenous force not identified
  - e.g., model: force DoD adoption by 2010
- Major adoption still does not occur until early 2019
- Data has reversed since this work done

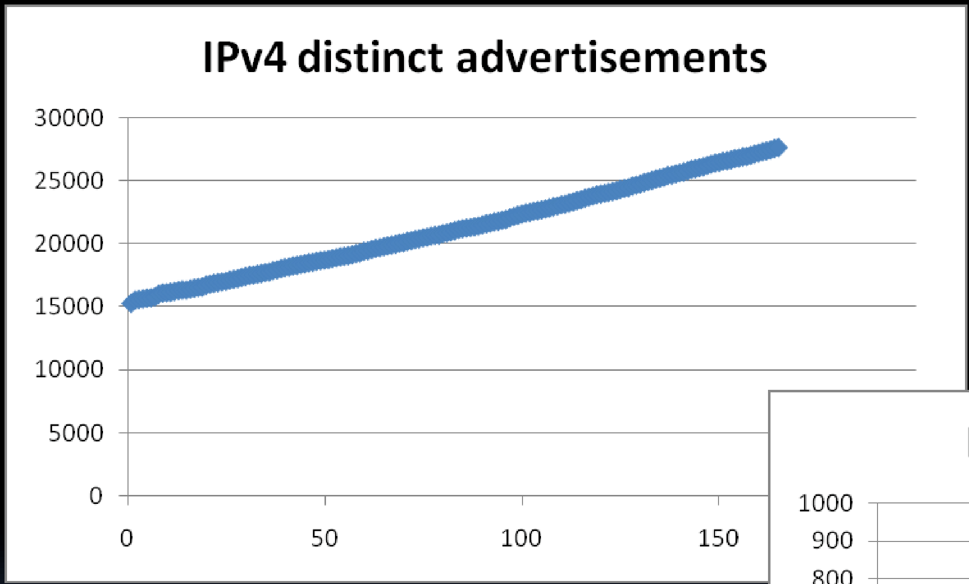


Forcing Function: Most Optimistic

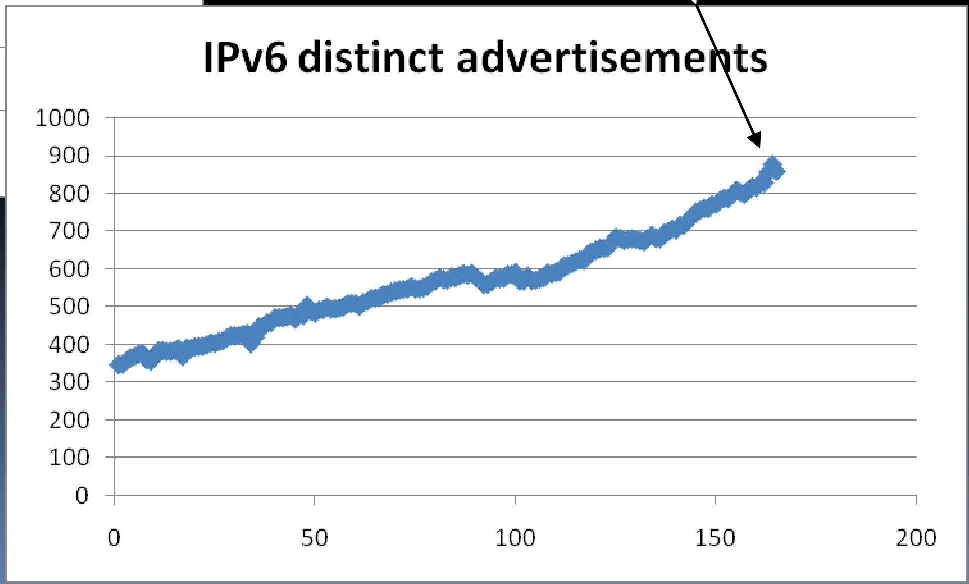
- 80% adoption in 8 years
  - **Most optimistic** that can be extrapolated from current data
- May not be sufficient



IPv4 versus IPv6 Routes Over Time

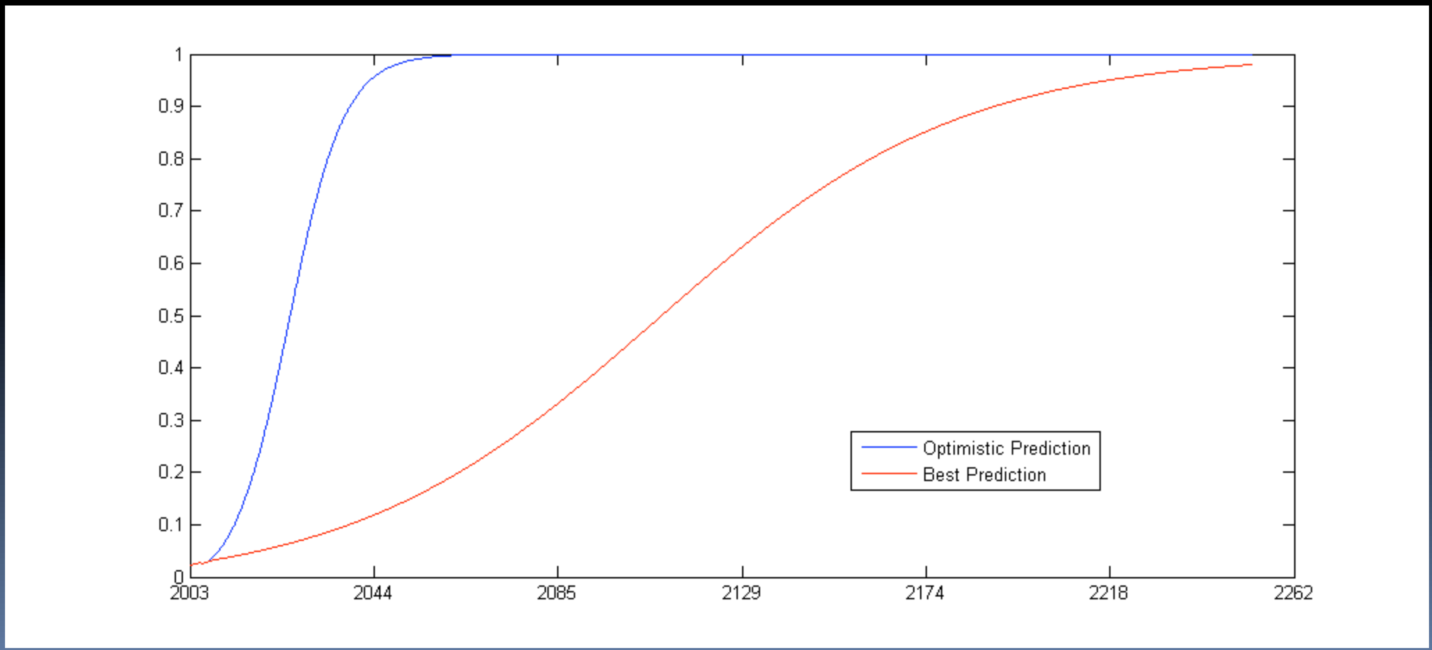


This upturn is the source of most optimistic possible with truncated data



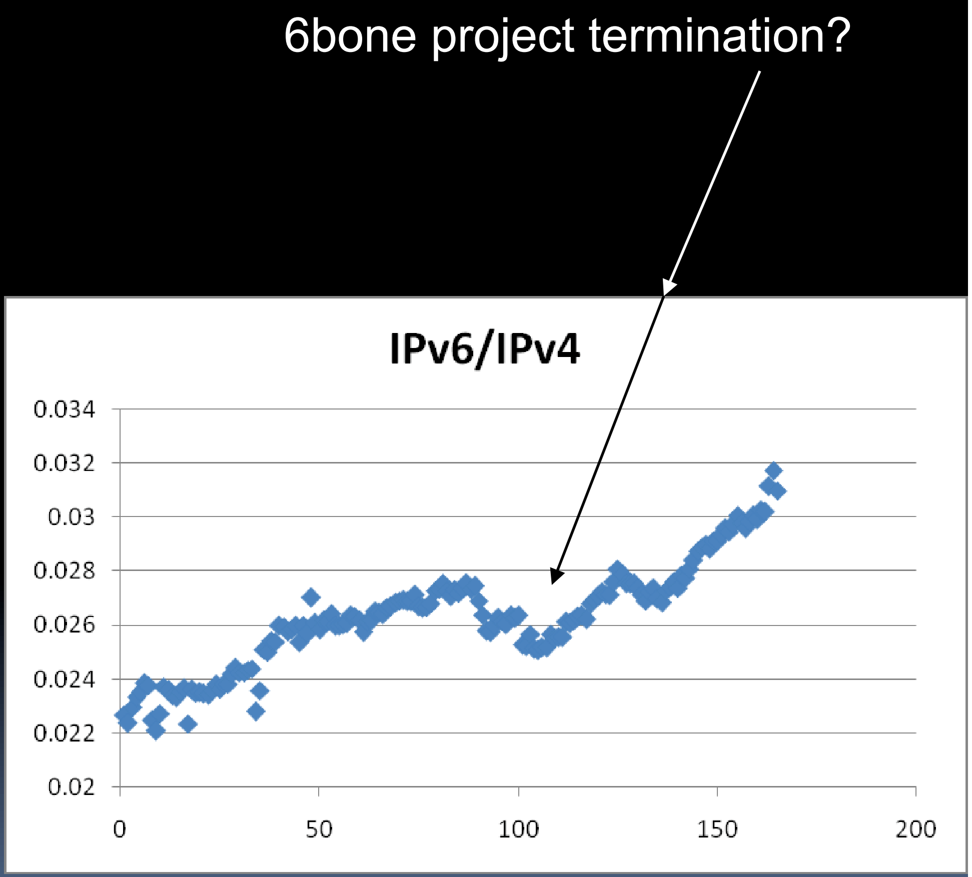
ASN Count with Best Fit

- One standard deviation from the follower coefficient
  - Best estimate with curve fit
  - Best possible result (coefficient + standard deviation)
- Results
  - 40 years to .....



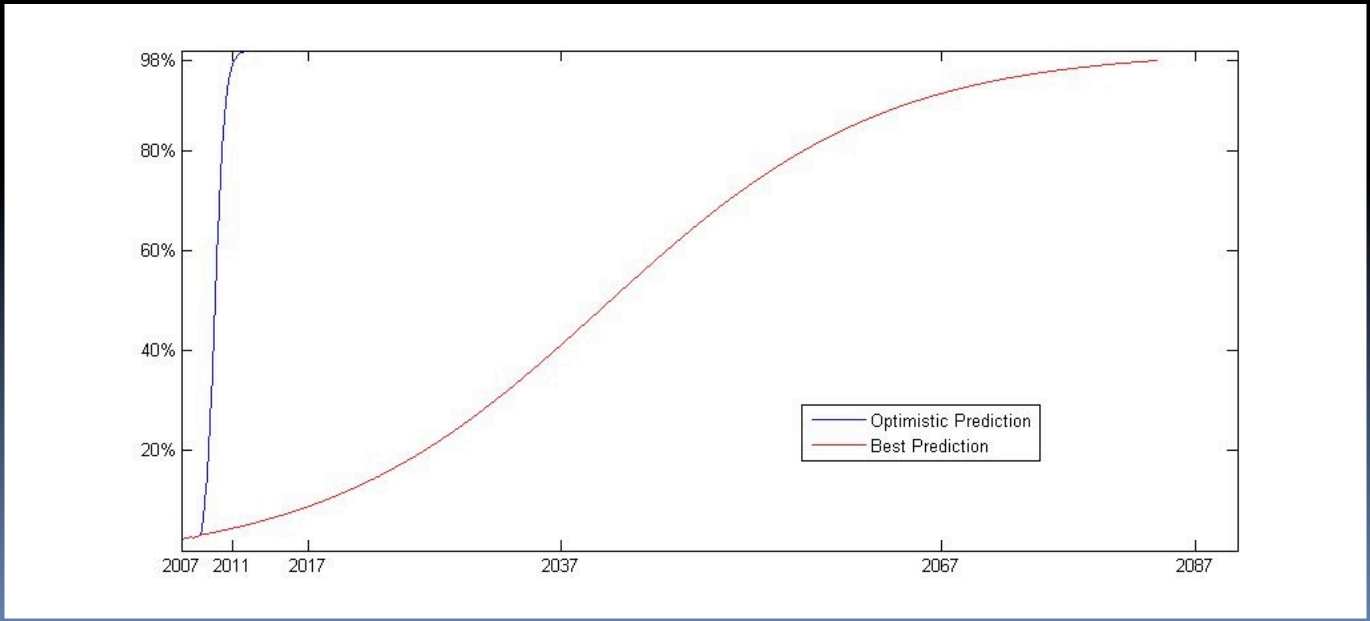
Which Months Matter?

- Results are very sensitive
  - Beginning point
  - Initial conditions
  - Coefficient varies
- Truncate data to five month window
  - Best possible of best possible result



ASN Count, Truncated Data

- Cut to last six months
- Varying the follower coefficient
  - Best estimate with curve fit
  - Best possible result (coefficient + standard deviation)
- Results
  - Between six and seventy years



Summary

- Route data
  - Worst case > 20 years
  - Best case 8 years, 2016
    - Truncating data severely + one standard deviation of coefficient

Summary

- ASN
  - No duplicates, arguably better fit
  - Worst case > 200 years
    - Data set to 2004 + one standard deviation of coefficient smaller
  - Best case 6 years, 2014
    - Truncating data to six months + one standard deviation of coefficient larger

Why So Long?

- Best case between 6 and 8 years
  - These are optimistic and uncertain predictions
  - But in ***no case*** does diffusion occur before exhaustion
- Lack of information
  - Invisible benefits, uncertain …
- Network externalities against early adoption
  - Not at tipping point, what is tipping point?

Why So Long?

- Misaligned incentive structure
  - Tacit knowledge loss
  - Testing costs
  - Endowment

Promoting IPv6 Adoption

- Government support of adoption
  - Subsidies decrease adoption costs
    - Increase incentives for production
    - Lower long-term costs of production, lower ultimate cost of adoption
  - Demand pull
    - Federal and state adoption to address network effects
  - Fines, tax credits, technical standards & requirements

State of the World

- Chinese, Japanese, and Korean governments leading the transition to IPv6
  - Incentives
  - Funding
  - Contractual obligations
- No data comparison
- Level of deployment in Europe called “imperceptible” in 2004 final report of the European IPv6 Task Force

Implications

- On a global scale IPv6 adoption benefits outweigh costs - but timely adoption …
- In the U.S. & Europe existing IPv4 infrastructure and high investment cost of switching are larger than in developing countries

Implications

- Potential implications for international competitiveness
  - Tacit knowledge
  - Support industries
  - Loss of lead in network science
    - Ubiquitous and mobile systems
    - Secure broadband penetration
    - Innovation enabled by end-to-end addressing

Why *Not* Pay Adopters?

- Solve the human problem
  - Certification of individuals IPv6 engineers
    - Leader certification
    - Team with universities
    - Define curriculum or knowledge base
      - CISSP model
        - Give it away free until people want it

Usability Matters

- Security has only recently discovered that usability matters
  - Formal studies of IPv6 configuration
  - Assist engineers with transition
  - Assist consumers with adoption
  - Merge with new services
  - Network engineers are users too

Solving the Lemons Problem

- Information availability
  - TCO Case studies
    - Mobility cost
      - Device fraud
    - Security cost

Market

- What problem is solved with market?
  - scarcity
- What problems are created with a market?
- How do you design a market?
    - Bundle of rights
    - Mechanism for market clearance
- Difficult challenges

Market Outcomes?

- Expensive IPv4
  - - Barrier to entry
  - - Endowment incents major players not to adopt
  - + Provides a price for comparison
- Cheap IPv4
  - Owners have little incentive to sell or switch, IPv4 unavailable
- Unavailable IPv4
  - - Barrier to entry
  - - Regulatory imperative
  - + Forced adoption of IPv6

Results Summary: Five Answers on IPv6 Diffusion

- What is a reasonable, available measure?
  - Routes and ASNs yield similar near-term results
- The diffusion uncertainty was bound and quantified given this data.
- There is no feasible path which results is less than years of IPv4/IPv6 co-existence. Decades is not unreasonable.
- Observations from economics of security applied to IPv6; implications enumerated.

References

- Economics of Information Security
  http://infosecon.net

- L. Jean Camp
  http://www.ljean.com