AI in Computer Networking



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Audio/Video recordings of this class lecture are available at:

http://www.cse.wustl.edu/~jain/CSE5700-25/

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Overview

1. Evolution of AI
2. Applications to Routing, Traffic Engineering, Security, and Management
3. Standards Activities: IETF, IEEE, …
4. Open Challenges

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Evolution of AI

- 1950: Alan Turing asked, "Can Machines Think?" This is considered the beginning of AI.
- 1956: The term "Artificial Intelligence" was coined at the Dartmouth Conference
- 1960-70: Rule-based systems, Pattern Matching, Signature-based
- 1980: **Machine Learning (ML)** with algorithms like decision trees, k-nearest neighbors (KNN), neural networks (NN). These need training (supervised learning)
- 2006: **Deep Learning (DL)** with Layered Neural Networks, Deep Convolutional Networks for Vision, Reinforcement learning, **Generative Adversarial Network (GAN)**. This is unsupervised learning.

Ref: M. Imran, "The Journey of AI: A Timeline from 1950 to 2025," https://www.linkedin.com/pulse/journey-ai-timeline-from-1950-2025-muhammad-imran-ub9nf/

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Evolution of AI (Cont)

- 2017: **Transformers** - A novel neural network architecture introduced by Google researchers for language processing (foundational technology behind LLMs and GPT)[1].
- 2018: **Generative Pre-Trained Transfer (GPT)** - Parallelization reduces the training time significantly, leading to Large Language Models (LLMs).
- 2024: Real-time multimodal agents – integrating vision, voice, and text for dynamic interaction.
- 2025: **Generative AI (GenAI)** – Can use learned knowledge to generate new content, e.g., draw a dog wearing a doctor's suit.
- 2025: **Agentic AI** - autonomous systems that can reason, plan, make decisions, and execute multi-step tasks with no human intervention.

[1]Ref: A. Vaswani, et al. "*Attention Is All You Need*." *Advances in Neural Information Processing Systems 30*, 2017, pp. 5998–6008. https://doi.org/10.48550/arXiv.1706.03762

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Evolution of AI (Cont)

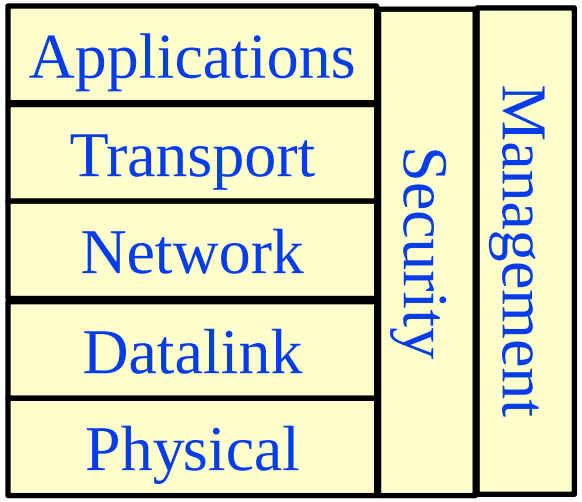
Agentic AI	Plan, Decide, Act Autonomously
Generative **AI**	Generate New Concepts
Real-Time Multi-Modal Agents	Integrated Voice, Video, and Data
Generative Pre-Trained Transfer (**GPT**)	Reduce Training Time ⇒LLM
Transformers	Transformers ⇒ Language
Deep Learning (**DL**)	Unsupervised Learning
Machine Learning (**ML**)	Supervised Learning

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Networking Tasks

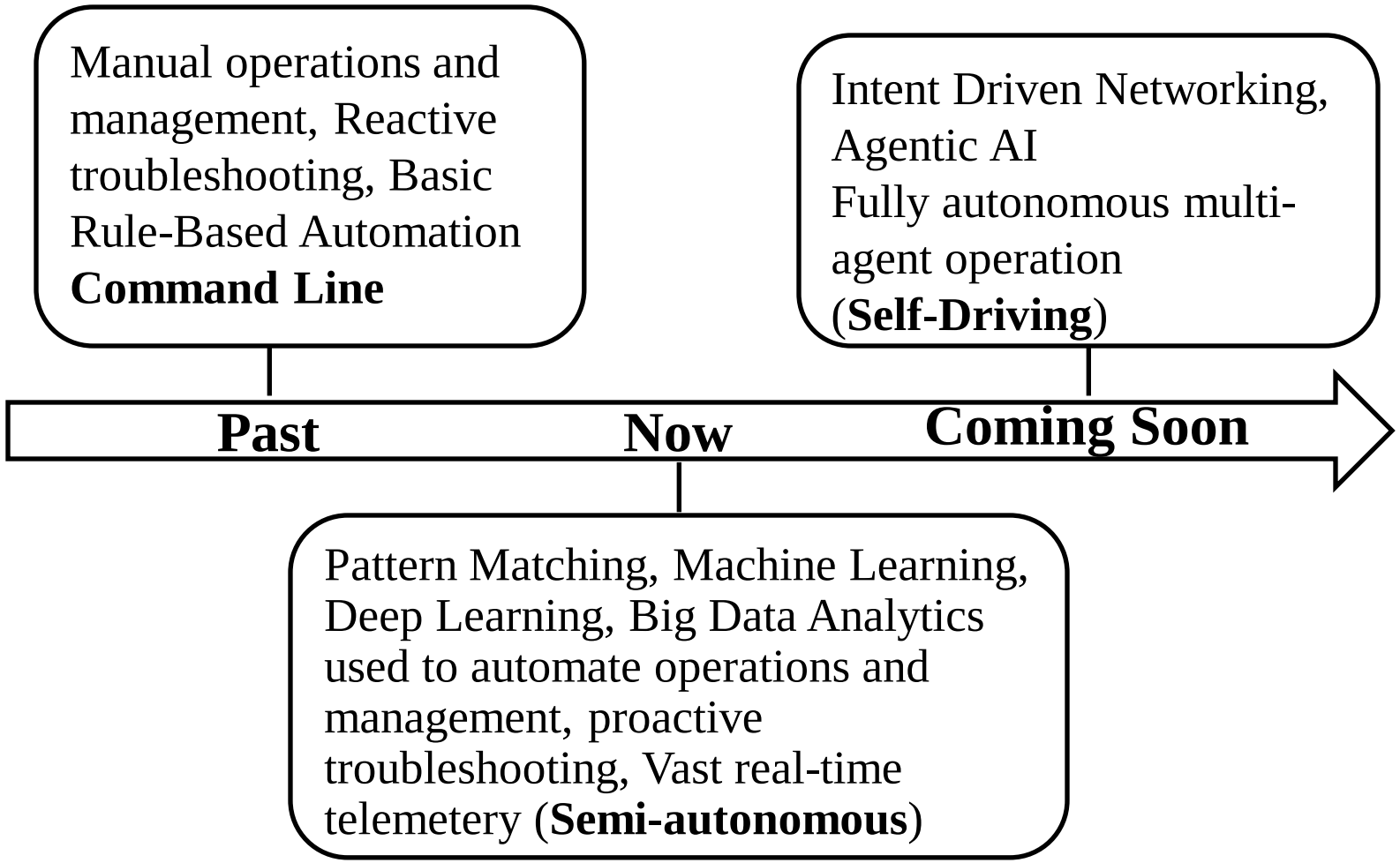
- Applications: Web service, Domain Name Service, …
- Transport: Flow control, congestion control, …
- Networking: making forwarding tables, longest prefix-search, …
- Datalink: VLANs, spanning tree, …
- Physical: Coding, Wireless (channel modeling), …
- Management: FCAPS – Faults, Configuration, Accounting, Performance optimization, Security
  - Security: Attack detection, prevention, and recovery
  - Faults: Detection and recovery
  - Configuration: network design, tower placement, fiber installation, …
- *Which of these tasks can be outsourced to AI?*



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Timeline of Networking Operations

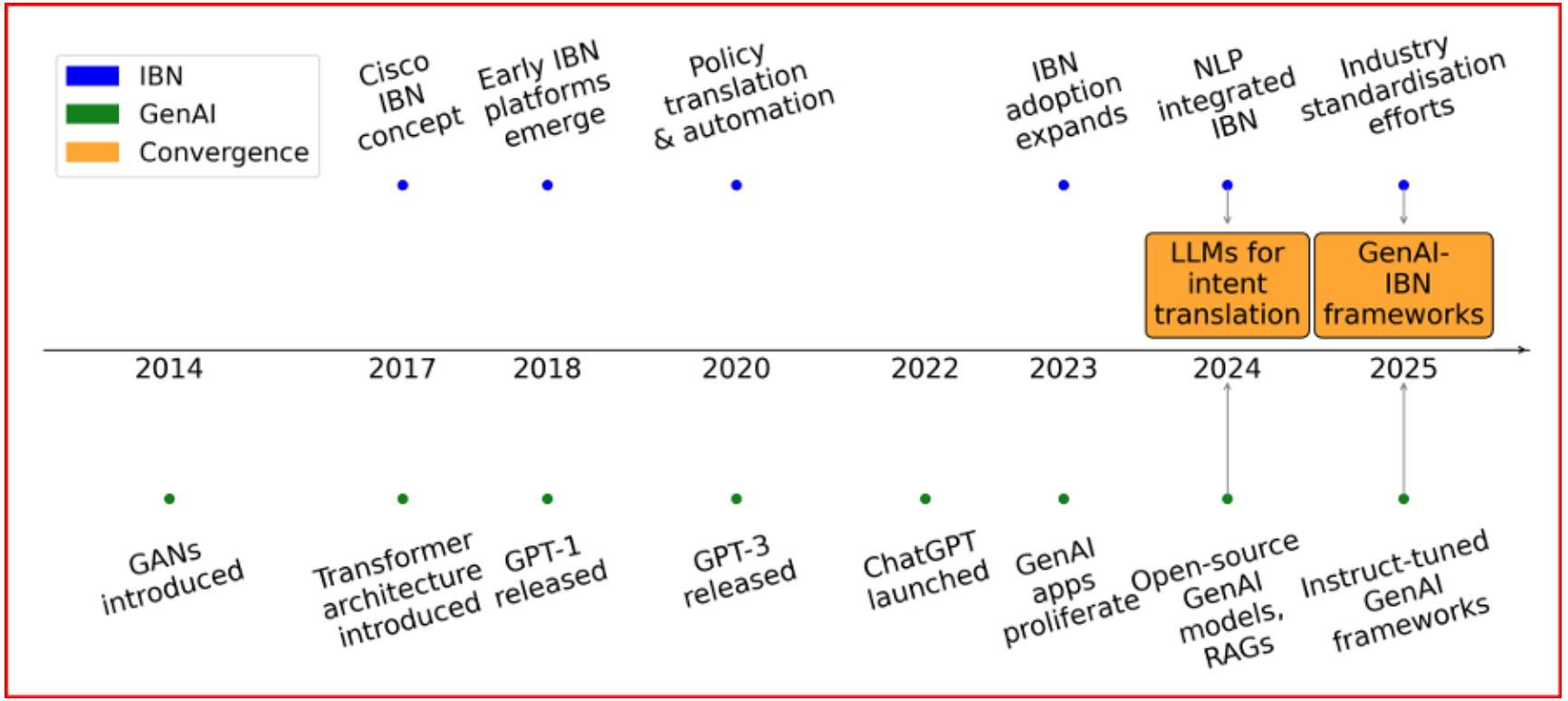


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AI and Networking Timeline

❑ Intent-based Networking (IBN) to GenAI Convergence



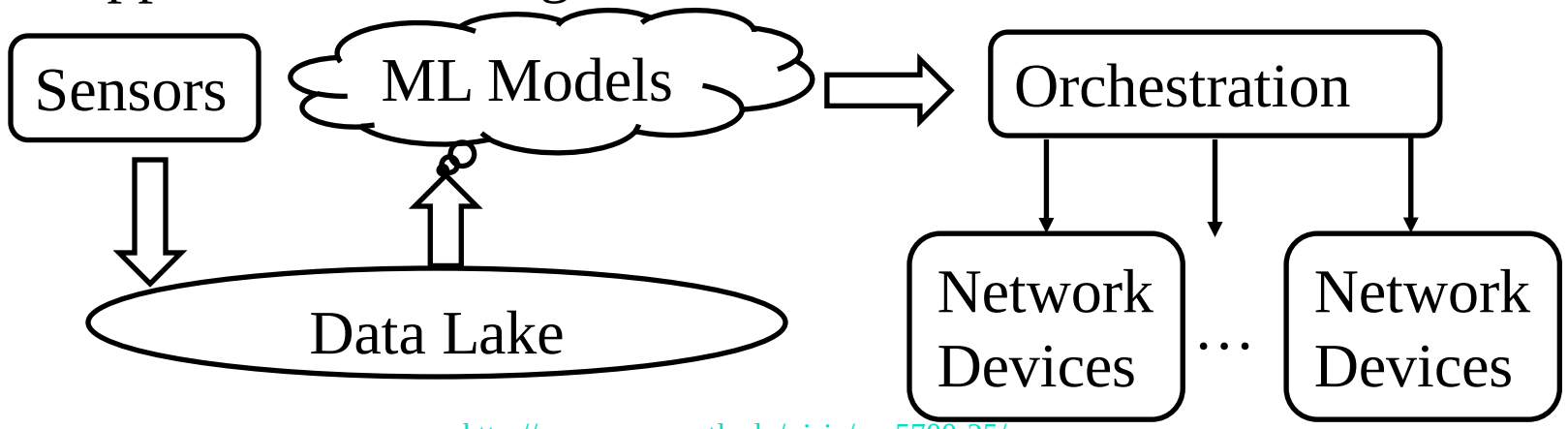
Ref: S. Kapoor, et al., "GenAI-powered Intent-Based Autonomous Networks: Standardisation Landscape and Emerging Industry Trends," Authorea 2025, https://www.techrxiv.org/doi/pdf/10.36227/techrxiv.175756256.63633045

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AI Driven Network Management

- Integrate AI in real-time analytics and operations using domain-specific ML models
- Example: **Cisco AI Canvas**
  - Allows policy orchestration and context-aware decision making
  - Supports Campus, Data-Centers, Clouds, Edge, and cross-domain
  - Supports intent recognition



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Cisco AI Canvas

- Generative AI dashboard for:
  - **NetOps**: Network Operations, automation and orchestration
  - **SecOps**: Integrate IT operations and security teams
  - **DevOps**: Collaborative software development combining developers and operations
  - Real-time analytics, and collaborative troubleshooting
- Uses Deep Learning and LLMs
- Works across on-prem, cloud, multi-cloud, and hybrid deployments
- **AgenticOps**: Autonomous agents that reason, act, and learn across domains

Ref: Cisco, "Announcing Cisco AI Canvas. Revolutionizing IT with AgenticOps." June 10, 2025, https://newsroom.cisco.com/c/r/newsroom/en/us/a/y2025/m06/announcing-cisco-ai-canvas-revolutionizing-it-with-agenticops.html

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Intelligent Routing with AI

- Classical routing uses Dijkstra, Bellman-Ford, Max-Flow, etc. Optimal for fixed configurations. Limited use for dynamic, multi-metric networks
- AI provides priority-based, learning-enhanced routing, e.g., Reinforcement Learning (RL)-adapted Dijkstra. Context-aware path selection.
- Multi-agent reinforcement learning for Distributed networks, context-aware quality of service, task allocations, trust, load balancing, and latency.

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AI-Enabled Traffic Optimization

- Dynamic traffic routing, load balancing, and congestion mitigation using ML, DL, and optimization algorithms
- Uses RNN, GAN, Hybrid-Neural Optimization, Reinforcement Learning
- Significantly outperforms classical optimization (Dijkstra, Max-Flow)
- Used by telecom carriers
- Can also be used in logistics, smart-city traffic management, and cloud applications

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Predictive Maintenance In Networking

- Analyze traffic flows, temperature, vibration, and power to predict device health
- ML models spot early warning signs of degradation by detecting anomalies/patterns
- Proactive Alerts, automated mediation, e.g., traffic rerouting, hardware replacement scheduling
- Continuous learning: System improves with feedback
- Leads to 99.999% availability, significant reduction in downtime, and cost reduction

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AI for Network Security

- Proactive detection, classification, and mitigation of new threats
- Can detect Malware, Advanced Persistent Threats (APTs), Distributed Denial of Service (DDoS), and insider attacks.
- Uses deep learning, anomaly/outlier detection, graph neural networks, and natural language processing (NLP) for phishing/social engineering
- Zero-Trust: Never trust, always verify. Assumes a threat could exist anywhere – inside or outside. Requires strict identity verification and authorization for every user and device. Repeat periodically.
- Real-time detection, rapid incident response, dynamic isolation.

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AI-Powered Anomaly Detection

- Traditional systems use static thresholds and rule-based triggers
- AI enables context-aware, adaptive anomaly detection
- Uses supervised (Support Vector Machine (SVM), Decision Trees, Deep Learning), Unsupervised (Clustering, Autoencoders), Hybrid, and Generative Adversarial Networks (GANs).
- Uses statistics across layers, time, and vendors
- Automated root-cause analysis and remediation (auto-heal, ticketing)
- Results in near 100% uptime

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AI-Driven Network Automation

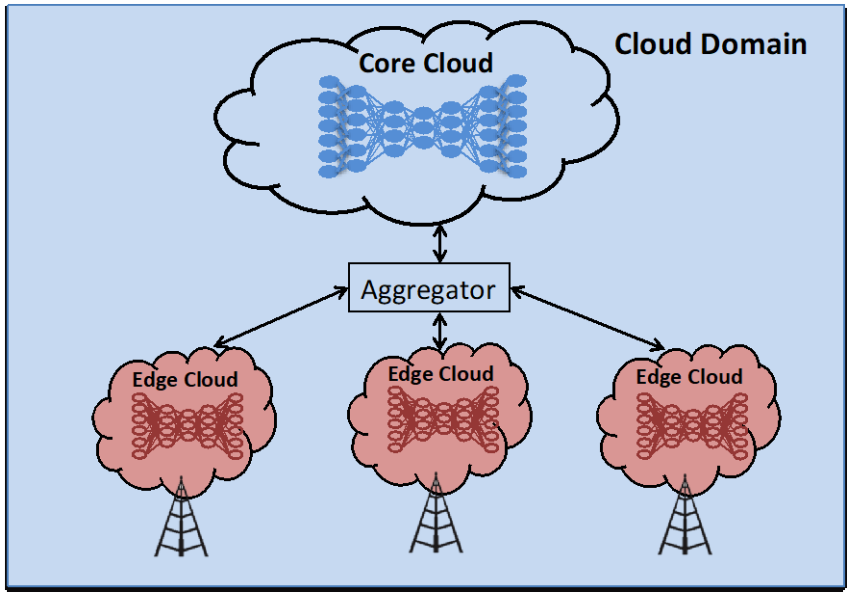
- Automate configuration, monitoring, troubleshooting, and even compliance.
- Eliminates human-in-the-loop for routine operations. Staff can focus on complex scenarios.
- Chatbot and voice-activated workflows (NLP-powered assistants).
- Intent integration, validation, deployment, and continuous assurance.
- Fast resolution, significant ticket reduction, major OPEX savings.

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Edge Computing and Distributed AI

- Moves machine learning to devices near the data generation:
  - IoT, Smart Cameras, Smart Phones, Wireless Access Points
- Only results are transmitted to the center => Reduces backhaul traffic, improves privacy, and ultra-low latency.



Ref: L. Gupta, T. Salman, A. Ghubaish, D. Unal, A. K. Al-Ali, R. Jain, "**Cybersecurity of multi-cloud healthcare systems: A hierarchical deep learning approach**," Applied Soft Computing (2022), 5 January 2022, http://www.cse.wustl.edu/~jain/papers/muse.htm

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Generative AI and Agentic AI

- Generative AI accelerates troubleshooting, configuration, documentation, and code generation via LLMs
- Agentic AI: Autonomous agents can reason, act, and collaborate. Perform intent-driven multi-step workflow execution.
- Example: Cisco AI Assistant

Ref: Cisco, "Unlock the Future of Network Management with AgenticOps,"
https://www.cisco.com/site/us/en/products/networking/offers/assets/ai-market-leadership.html#tabs-9da71fbd27-item-1288c79d71-tab

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AI in 6G and Next-Gen

- In 6G and next-generation networks, AI would be foundational at every layer and every node.
- Enabling end-to-end closed-loop automation for resource allocation, fault recovery, and protocol adaptation.
- May include Edge AI, federated learning, for privacy, locality, and resilience
- AI-native Radio Access Networks (RANs), core, and service orchestration frameworks.

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M. Yu, et al, "AI Agent Use Cases and Requirements in 6G Network," IETF draft, last updated Jul 7, 2025. https://datatracker.ietf.org/doc/draft-yu-ai-agent-use-cases-in-6g/

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AI Activities at IETF

- Internet Architecture Board (IAB) convened a Workshop on AI-CONTROL (aicontrolws) in September 2024.
  - Need to standardize robots.txt for clear communication between content publishers and AI model trainers.
- **AI Preferences working group (aipref):** Web and Internet Transport area. How content is collected and processed for AI model development, deployment, and use.
  - Will prevent improper use of Internet content for training LLMs.
- There are many other Internet drafts related to AI submitted to various IETF working groups and IRTF research groups

1. M. Nottingham and S. Krishnan, "IAB AI-CONTROL Workshop Report," IETF Draft, Last updated Sept 10, 2025, https://datatracker.ietf.org/doc/draft-iab-ai-control-report/
2. P. Keller and M. Thomson, "A Vocabulary for Expressing AI Usage Preferences," IETF draft, last updated Oct 28, 2025, https://datatracker.ietf.org/doc/draft-ietf-aipref-vocab/
3. G. Illyes, and M. Thomson, "Associating AI Usage Preferences with Content in HTTP," IETF draft, last updated Oct 28, 2025, https://datatracker.ietf.org/doc/draft-ietf-aipref-attach/

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AI Activities in IEEE

- Demand for AI in the data center is exploding
- Major concern is for Ethernet to capture the AI datacenter market.
  - Currently divided among Ethernet, Infiniband, and NVLink (Nvidia Link)
  - 400-800 Gbps copper for NICs and ToR switches
  - 400-800 Gbps fiber for aggregation switches

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Ref: IEEE, "IEEE 802.3 Ethernet for AI Assessment Reflector Information," Ethernet for AI Assessment Reflector Information
IEEE, " IEEE 802.3 New Ethernet Applications Ad Hoc - Ethernet for AI Assessment," https://www.ieee802.org/3/ad_hoc/E4AI/index.html

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AI Activities in ITU

- ITU has published 120 standards on AI.
  - 130 more under development
- AI can be used for early tsunami detection, mapping landslides
- Global cooperation on AI-enhanced hazard resilience

- Similar work in 3GPP, ETSI, …

Ref: ITU, "Standards help unlock trustworthy AI opportunities for all," https://www.itu.int/hub/2025/04/standards-help-unlock-trustworthy-ai-opportunities-for-all/

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Open Challenges

- Explainable, auditable, and trustworthy AI to ensure decisions can be traced and validated.
- Scaling, governance, and error mitigation of Multi-agent collaborations and agentic architectures
- Protecting telemetry and training data for privacy
- Compliance with laws

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Laws

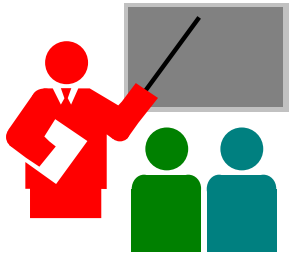
- **GDPR**: General Data Protection Regulation created by the European Union. Individuals control their personal data and set strict requirements for how companies collect, process, and store data
- **FedRAMP**: Federal Risk and Authorization Program. US Government compliance program for cloud products used by Federal agencies.
- **EU AI Act**: Assess the risk of each AI decision. Heavy fines of 35M Euro or 7% of an organization's global turnover

Ref: IBM, "Getting Ready for the EU AI Act, Phase 2: Risk-Assess and Categorize," https://www.ibm.com/account/reg/us-en/signup?formid=urx-53079

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Summary



1. AI has moved from supervised machine learning to autonomous Agentic AI
2. AI is used in each layer of networking, including routing, traffic engineering, security, and operations.
3. Autonous network operation is still in works.
4. There are significant challenges related to explanability, trustworthiness, and auditability of AI actions, and meeting legal requirements.
5. All networking standards bodies are discussing the use of AI

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- Deep Learning, https://www.deeplearningbook.org/
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- Transforming Urban Mobility: AI-based Traffic Optimization, https://link.springer.com/article/10.1007/s11831-025-10297-6
- AI for Complex Network: Potential, Methodology, and Application, https://arxiv.org/abs/2402.16887
- Artificial Intelligence advances in anomaly detection for telecom networks, https://link.springer.com/article/10.1007/s10462-025-11108-x
- Evolving Towards Artificial-Intelligence-Driven Sixth-Generation Mobile Networks, https://www.mdpi.com/2076-3417/15/6/2920

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- AI-Enhanced Predictive Maintenance: Case Studies, https://moldstud.com/articles/p-case-studies-achieving-success-with-ai-enhanced-predictive-maintenance
- The 10 Hottest AI Networking Tools Of 2025 (So Far), https://www.crn.com/news/networking/2025/the-10-hottest-ai-networking-tools-of-2025-so-far
- How AI Is Transforming Network Security And Optimization, https://www.forbes.com/councils/forbestechcouncil/2025/10/16/how-ai-is-transforming-network-security-and-optimization/
- Cisco AI Canvas, https://newsroom.cisco.com/c/r/newsroom/en/us/a/y2025/m06/announcing-cisco-ai-canvas-revolutionizing-it-with-agenticops.html

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Wikipedia Links

- https://en.wikipedia.org/wiki/Adversarial_machine_learning
- https://en.wikipedia.org/wiki/Applications_of_artificial_intelligence
- https://en.wikipedia.org/wiki/Artificial_general_intelligence
- https://en.wikipedia.org/wiki/Artificial_intelligence
- https://en.wikipedia.org/wiki/Artificial_Intelligence_System
- https://en.wikipedia.org/wiki/Convolutional_neural_network
- https://en.wikipedia.org/wiki/Deep_learning
- https://en.wikipedia.org/wiki/Explainable_artificial_intelligence
- https://en.wikipedia.org/wiki/Generative_adversarial_network
- https://en.wikipedia.org/wiki/Generative_artificial_intelligence
- https://en.wikipedia.org/wiki/Graph_neural_network

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Wikipedia Links (Cont)

- https://en.wikipedia.org/wiki/History_of_artificial_neural_networks
- https://en.wikipedia.org/wiki/Machine_learning
- https://en.wikipedia.org/wiki/Neural_network
- https://en.wikipedia.org/wiki/Neural_network_(machine_learning)
- https://en.wikipedia.org/wiki/Outline_of_artificial_intelligence
- https://en.wikipedia.org/wiki/Recurrent_neural_network
- https://en.wikipedia.org/wiki/Software_agent
- https://en.wikipedia.org/wiki/Symbolic_artificial_intelligence
- https://en.wikipedia.org/wiki/Timeline_of_artificial_intelligence
- https://en.wikipedia.org/wiki/Transformer_(deep_learning_architecture)
- https://en.wikipedia.org/wiki/Types_of_artificial_neural_networks

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Acronyms

- 3GPP Third Generation Partnership Project
- AgenticOp Agentic Operations
- AI Artificial Intelligence
- APT Advanced Persistent Threat
- DDoS Distributed Denial of Service
- DevOp Joint Development and Operations
- DL Deep Learning
- ETSI European Telecommunications Standards Institute
- EU European
- FedRAMP Federal Risk and Authorization Management Program
- GAN Generative Adversarial Network
- GDPR General Data Protection Regulation
- GPT Generative Pre-Trained Transfer
- IAB Internet Architecture Board

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Acronyms (Cont)

- IBN Intent-based Networking
- IEEE Institution of Electrical and Electronics Engineers
- IETF Internet Engineering Task Force
- IoT Internet of Things
- IRTF Internet Research Task Force
- IT Information Technology
- ITU International Telecommunications Union
- KNN k-Nearest Neighbors
- LLM Large Language Models
- ML Machine Learning
- NetOp Networking Operations
- NIC Network Interface Card
- NLP Natural Language Processing
- NN Neural Networks

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Acronyms (Cont)

- NVLink Nvidia Link
- OPEX Operational Expenses
- RAN Radio Access Network
- RL Reinforcement Learning
- SecOp Security Operations
- SVM Support Vector Machines
- ToR Top of the Rack
- VAE Variational Autoencoder
- VLAN Virtual Local Area Network

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Related Modules



CSE 567: The Art of Computer Systems Performance Analysis
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw





CSE 570: Recent Advances in Networking (Spring 2013)
https://www.youtube.com/playlist?list=PLjGG94etKypLHyBN8mOgwJLHD2FFIMGq5

CSE571S: Network Security (Spring 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u





Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw

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