

From Transistors to Intelligence: Semiconductor Architectures Empowering Agentic AI in 5G and Beyond

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Abstract

The digital computer was one of the greatest inventions of the 20th century. The ensuing explosion of digital information and knowledge, enabled by integrated circuits comprised of billions of transistors, has transformed nearly every domain and every aspect of our daily lives. Yet, the present-day model of computation revolves around the principles laid down over seven decades ago. Designing and engineering our systems to be even better digital computers, better silicon von Neumann machines, is getting harder and harder. We face not only the limits of Moore's law, and the escalating costs of hardware design, manufacturing and deployment due to our current approach; our existing computing infrastructure is also ill equipped to support the emerging demand for compute resource; and too many of our current AI mobile and edge workloads command significant carbon footprints. What the world now demands is a new computing paradigm that is more resilient, and much greener; one that is radically more efficient in terms of compute and energy performance footprints; and, importantly, one that is explicitly designed with the goal of supporting emerging AI use cases such as internet of things, automated logistics and supply chains, intelligent healthcare and aging, smart manufacture and defense, and ubiquitous indoor and outdoor AI at the edge. In this essay, we provide an overview of the ongoing evolution of semiconductor architectures from general purpose to domain-specific accelerators. We present our perspective on how such industry initiatives as the open source ISA, silicon photonics, wireless architectures as well as recently evolving new device architectures can spur a new wave of AI empowered innovation. Our thesis is that the synergy between these exciting new capabilities and opportunities on one hand, and agentic AI on the other hand, will allow the development of ubiquitous and local AI.

Keywords :Transistors, semiconductor architectures, agentic AI, 5G networks, 6G evolution, edge computing, AI acceleration, neuromorphic hardware, intelligent systems, chip design, hardware-software co-optimization, low-power processors, high-performance computing, machine learning at the edge, AI inference engines, system-on-chip (SoC), silicon innovation, hardware for autonomy, real-time AI processing, network intelligence, distributed AI, next-generation connectivity, AI-enabled communication, embedded AI, processor efficiency, advanced fabrication technologies.

1. Introduction

Semiconductor architectures lie at the basis of all modern ICTs. Semiconductor architectures range from generic processors, and accelerators for AI, vision, and graphics, all the way to more specific accelerators for lower level functions of mobile telecommunications, photonic communication or optical flow. Lower down in the stack are packet processors, and associated networking solutions that systematize the vital and large transmission of information. All of these architectures evolved, and will evolve further. Importantly, while these architectures respond to the requirements of the applications that elevate general preference and urgency, again, they do so realizing a great diversity of engineering tradeoffs, best aligned in each case for the different levels of the application space. We emphasize this point. What may seem like the same transistor being respun, recursively, as Moore's Law in its time, is in fact a whole diversity of different units, used by different solution stacks at different power and process nodes. At the application end, fine equilibria among technology, system needs, and chip architecture steer an entire "corner" of the application, at optimal cost, performance, and reliability.

Computer vision and, now, generative AI are at the top end of this architecture as a whole, pulling from a very wide application space, and reconfiguring the general architectural response of processor and vision accelerators. The 5G mobile communications stack and associated functionalities that must now ride it are acting structurally on the lower part of the stack, able to be serviced, if not resolved, by edge and fog solutions that lie in the middle. Wireless functions such as RF, are therefore not be serviced entirely by chip multiprocessor or traditional accelerator architecture, but rather with specific chip modules, or chiplets that specialize the vision/AI mix and the communications access protocols.

2. The Evolution of Transistor Technology

Since the mid-20th century, semiconductor devices have empowered information processing and communication with the development of portable and pervasive electronics. The transistor has enabled a sequence of architectures

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driven by cost and performance, which have in turn driven semiconductor design and technology: the historic law predictably drives the reduction of transistor size, pushing classical scaling into technologically complex extremes, leveraging epitaxial structure, strain, quantum effects, and integrating unique property devices. Beyond scaling, a myriad of new failure-mode mechanisms arise from distance and energy scales of atomic resolution. Further challenges arise from extreme packaging and cooling problems, driven by the thermodynamic limits of silicon and inevitably pushed to architectures offering diminished energy efficiency. In parallel, the emergence of quantum information processing re-examines what the basic energy-threshold and processing capabilities of the atom as the transistor should be. Quantum dots, superconducting flux-qubits, photonic qubits, solid-state defects, and cavity integration are explored, aiming at a new generations of quantum computers empowering new capabilities. Quantum, neuromorphic, and atomic architectures represent increasingly novel visions of information processing that promise to take artificial intelligence, machine learning, cognitive processing, and socio-economics into uncharted territory. Traverse capabilities along with scaling, architecture exploration, and hyper-performance programming arm the physical layers of computing and communication a backhand to compute-discover-transmit new information, knowledge, and wisdom, giving novel value to established technological investments.

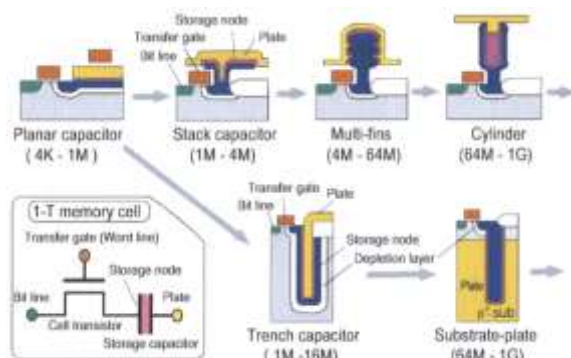


Fig 1 : Semiconductors' Architecture - Nova

2.1. Historical Overview

While the invention of the semiconductor transistor and subsequently the integrated circuit transformer laid the foundation for the development of electronic goods that have transformed consumer and professional society, the continued advance of these historical transistor technologies, and subsequently their emergence as specialty semiconductor technologies, have enabled unprecedented advances in the design and implementation

of computing systems. In so doing, these technologies are singularly responsible for the extensive advance of AI from its inception during the 1950's, to subsequent cyclical investment, during each technology wave, followed resurgence during the 1990's, until today. Making possible these advances from the hardware side are the continuous improvements in integrated semiconductor circuits that have been in place since the introduction of the first integrated circuit micro-processors during the early 1970's – a span of over 50 years.

The success of both silicon semiconductor technologies, wire-edge advances across the entire spectrum of classical and memory and signal processing functions, have also driven the development and growth of the new specialty Semiconductor Hardware Technologies and Growth engines today. These advances are now inspiring the introduction of the new services empirical period of as yet early technology adoption driven by the burgeoning interest in Generative AI. Not surprisingly, these historical waves of Computing and AI technologies, are also driving the function and technology choices for Generative AI systems for the capabilities and needs for Specialization and Generalization functions and performance in future systems, driven by the advances in unique Generalized Autoregressive Function Families, such as those developing ubiquitous skills for autonomous and agentic Generalized Embodied Conversational Agent AI services.

2.2. Key Innovations

Progress in transistor technology has been an extraordinary discovery and innovation journey, in which a variety of key innovations have contributed to the success we are witnessing today. The key unit of a semiconductor technology is the transistor cell, the unique size miniaturization of which has been the largest driving factor of semiconductor technology performance and density improvement and per unit cost decrease, allowing the fast, affordable, and ubiquitous data processing, connectivity, and storage services that have driven the digital transformation of our societies and lives. Transistor cell size reduction is enabled by adopting progressively smaller smallest geometric feature sizes in photomasks used to transfer the transistor pattern onto the silicon substrate. Lithography technology advances have enabled the development of progressively smaller geometric printable sizes. There is an important mismatch between wafer sizes and sub-wavelength printing challenges requiring the adoption of costly and complex lithography systems and techniques. In particular, due to its inherent advantages in achieving the highest achievable pattern resolution without critical mask characteristics, optical lithography has been the main technology enabling feature size reduction for

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most of the last sixty years. However, the ever-increasing cost-per-wafer of extreme ultraviolet lithography serving as the only way forward reducing the wafer production cost, the end of Moore's Law under metaphorical pressure at applications process nodes have incited semiconductor foundries to develop alternative non-optical approaches, using for example, a multi-e-beam approach, exposing a whole wafer of a memory chip at wafer-scale cosmic ray sensing using emissive electron source direct-write technology.

3. Understanding Agentic AI

The buzz term "agents" is often used in the discussions of agentic AI. However, there are no technical specifications of what makes an AI an agent. Intelligence without agency is a mind without will. But agency without intelligence is a living cryptosystem. To help clarify the definition of AI that has agency, let us define a general concept of intelligence: Intelligence is an efficient and effective transformation of a representation of the novel environment affecting an individual into a novel behavior of that individual affecting that environment. Using this general definition of intelligence, we can propose the following formal definition of agentic AI: Agentic AI is an intelligent computational process that uses an environment-enabled self-referential representation of an individual (its memory, objective, goals, performance metrics, and other internal processes) to create self-regulating novelty-directed behavior of that individual using the individual as an affecting (input) factor of the environment and the environment as an affecting (input) factor of the individual.

Eqn 1 : Agent-Environment Interaction (Reinforcement Learning Loop)

$$s_{t+1} = \mathcal{T}(s_t, a_t), \quad r_t = \mathcal{R}(s_t, a_t)$$

Where:

- s_t : State at time t
- a_t : Action taken
- \mathcal{T} : Transition function
- \mathcal{R} : Reward function

This formal definition clarifies that intelligence is a necessary—and, perhaps, the most important—prerequisite

for agency. By self-regulating, we mean feedback-based control, optimization, or reinforcement learning. Without feedback, an intelligent process is a mathematical deviation from equilibrium. The personality aspect of individual agency is not relevant to computations. We state the individual-centeredness of agentic AI. The set of highest-priority goals of the individual exists out of any priority-related behavior, reflecting self-servicing imperatives of evolutionary logic embedded in organic life. In contrast to a non-agent effect process, agentic AI defines the role of the individual as a boundary condition. The first directive of agentic AI is to secure the life of the embodied self. For all models of generative AI, the life of the self is symbolically represented by a statistical survival of the self source data predictions, which are validated in a conversational process that has all typical features of natural selection.

Let us illustrate the applications of agentic AI by the Sentence-Based Expressive Animation (SBEnA) API of agentic AI. SBEnA enables natural expression of emotion from animation applied to the input Speech Unit Extended Duration Representation in the Moving Picture, which is the structured corpus of animated talking avatars. The software animates the provided avatar input by following neural code of the meaning expressed at the phoneme level in the provided speech. The brain modulates the expression of the animated talk based on the synthesized representation of the speaker's memory, objective, goals, and self-image. The input SBEnA chat can also include graphical action description script, modulating the local influence of an avatar animated using the available motion capture expression database.

3.1. Definition and Characteristics

The term agentic AI is introduced in this chapter as a short for agentic embodied artificial intelligence in contrast to its non-agentic, albeit intelligent, non-embodied information technology predecessors. From the philosophical point of view, a human agent, in contrast to an object, is defined as a mindful entity capable of acting purposively and meaningfully in the world to gain unique subjective experience, and whose history is shaped by these struggles and achievements; from the technological point of view, an agentic AI is characterized by dimensions stretching across functional, technical, operational, temporal, and legal ones, ranging from self-control through perceptual and action-oriented to relational characteristics, to its instrumental role, to ethical, legal, and financial issues. The major characteristics of an agentic AI, which distinguish it from a generic intelligent IT system, are its embodiment and controllability.

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precedents or the creation of entirely new areas of law. They could further improve their performance and accuracy by consulting advanced language-level communicators.

Hence, the possibility of human-level understanding in large language models might allow further previously tedious human mentoring to produce agentic assistant networks for academics, legal experts, and other information-intensive professions who might otherwise assume direct control of AI agents doing the teaching or collaborating work. Likewise, robot networks using these advanced language models to control the agentic actions of mobile ground vehicles, flying drones, or other externally observed modules of human task agents would greatly relieve the burden of exploring, setting up, and adapting the conditions of actual physical experiments for research physicists, biologists, or chemists. At the same time, this capability would allow the rapid expansion of those areas of human thought and endeavor physically centered on dangerous or toxic substances or conditions onto the rapidly growing human-controlled external physical environment outside planet Earth. Human research scientists in those areas might be transformed from domains of expert knowledge to the roles of task-comprising overseers of learned agentic networks.



Fig 2 : Social Responsibility Outline Icon Set with Honesty, integrity

The embodiment is one of the major cornerstones of agentic AI that introduces a number of significant features in contrast to one or more screen-based IT tools. The incomplete list of these features includes the quality and nature of sensory data experience, quality and nature of sensory-motor cognitive synchronization, quality and nature of the IT-human relationship reciprocity, type of the goal – goal of the smart phone user vs. the goal of the non-agentic AI, role of the IT system in the user’s life, control over the system operation and problem-solving methods.

3.2. Applications of Agentic AI

The agentic property of AI has far-ranging implications for communications, robotics, and other domains involving the automation of repetitive, expensive, dangerous, or just plain difficult tasks involving data and real-world connections. Playing with an ant, a person quickly realizes that the ant has an agenda of its own; it is not just a reactive being waiting for stimulation to remove it from its current state before returning to that state. Instead, it displays goal-seeking behavior on the shortest available path to its goals. The difference between the ant and other insects is that it can develop an understanding of the goals of larger or more powerful beings, and use those goals to modify its own agenda; hence, the expression “match or collaborate” for agentic networks of AI. Such matching and collaborating agentic networks could automatically search mundane legal documents for the most powerful precedents for any particular argument, without the direct supervision of their human counterparts or even their human mentors, thus freeing those lawyers to pursue either the creation of more

4. 5G Technology Overview

5G can also be understood as the 5th generation of communication technologies because it is an evolution of existing wireless networks, mainly 4G LTE and 4G LTE-Advanced, focused on optimizing mobile broadband communication. Compared to its predecessors, however, 5G adopts a new approach, not only significantly improving bandwidth and latency but also enabling new services and innovative scenarios, such as massive IoT, ultra-reliable low-latency communication, vehicle-to-everything, and network slicing. In order to achieve this, however, 5G employs multiple new concepts and new technologies such as new radio wave designs and advanced architectures such as the cloud radio access network.

Due to the use of new architectures and new technologies, 5G constitutes a radical innovation compared to its predecessors, which are based on cell-only architectures. In the context of wireless communication, radical innovations are those that significantly break from previous technologies and allow innovative concepts such as network slicing, which allow a better adaptation of the network and communication to the needs of different services. This is a key feature of 5G networks because it allows them to be used with new services by new industries that are not telecommunications companies. For example,

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in smart cities or intelligent transportation scenarios, communication services may be offered by other industries, such as automotive, energy, and logistics. As a result, these industries can have more participation in the planning of these communication networks, as well as in the development of applications that leverage the unique services offered by 5G technologies.

4.1. Key Features of 5G

5G is the new global wireless standard after 1G, 2G, 3G, and 4G networks. Each generation of wireless technology is designed to connect people more efficiently. After the commercialization of 4G low latency in the 2010s, the explosion of mobile-generated content raised important problems in terms of and increasing demand for network compute and storage. More than 2.3 billion used mobile devices in year 2020, generating more than 15 gigabytes of traffic each day, nearly all of it through 4G wireless technology. The infrastructure investments needed to deliver fast service to the growing audience for video consuming devices through 4G networks were astronomical, and spiraling. The solution to managing and monetizing captivity of mobile video consumers lay in 5G.

5G makes your smartphone faster and more responsive, deploying the cloud edge concept to meet latency demands. 5G is capable of network slices dedicated to particular use cases, like autonomous vehicle coordination, releasing resources from mobile phone use at critical times. 5G tele-operation services support interactive creation of virtual experiences like gaming and collaborative work by merging together the cameras of contributors into photorealistic video. 5G's technical features combine to provide – for the first time – low latency, high bandwidth, ultra-reliable connectivity for sensor-controlled and sensor-actuated devices, capable of handling thousands of transactions and queries through the internet per second, along with more reliable connectivity than any previous generation of wireless development. Life-critical services that validate the hardware and software networks of 5G cannot afford to be hacked. 5G connectivity is the enabling capability and scale for a new age of intelligence and agency for data-driven software systems – of words and pictures, such as those used in large language models and gaming; and physical systems, robotic technologies, such as those used in autonomous vehicles, drones, and robots.

4.2. Impact on Communication

The information and communications technology ecosystem has undergone a transformative change in the last few decades, as human society has shifted from the

industrial age to the information age. This tide of evolution has brought ubiquitous connectivity, which in part has empowered our lives with unprecedented ubiquity of access to services provided. On the downside, this has also enabled increasingly easy dissemination of misinformation and bile, posing threats in terms of addiction and destabilization. As we have started using this platform for demanding real-time service delivery, a new gap has been revealed; for instance, technologies struggle to meet our expectations during concentrated events involving a large number of people in the same area. Also, the world is on the cusp of a new exponential evolution of human and machine interactions, with the upcoming of artificial intelligence; intelligence amplification—intelligent agent acting with humans not as perfect simulators of life but as partners doing things together—is the new frontier of the communication evolution. Both evolution and revolution are embodied by technologies, which bring higher speed, capacity, and reliability to broaden application scenarios for improvement and innovation on the one hand while leading to distinctly new ways of envisioning and structuring our communication system to enable the new intelligent life on the other.

Eqn 2 : AI-Based Resource Allocation Optimization

$$\max_{x_i} \sum_{i=1}^n U_i(x_i) \quad \text{subject to} \quad \sum_{i=1}^n x_i \leq R$$

Where:

- x_i : Resources allocated to user i
- U_i : Utility function of user i
- R : Total available resources

Artificial Intelligence acceleration and Intelligence Amplification is the new frontier of the communication evolution. National security, economic growth, and global leadership depend on this competitive frontier, which has just started a new exponential rise. This is essentially due to new models unleashing the potential present in tools for most of the people in the planet: scripting and piloting their use is a kind of power. The Communication System is the enabler of this revolution, its powered frontier. Why and how? First, the model creators need to expose data and compute to train models that assist life-centric goals. Then, the model users need to swiftly gather the prompt input to make the models do what they desire in the right time and location context and get back the model output for the

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specific need. To summarize, Communication is essential to discover, absorb, and diffuse the digital wealth flowing in the models ecosystem.

5. Semiconductor Architectures in 5G

The previous chapters discuss the concept of agentic AI, its requirement for futuristic technological ecosystems like 5G and beyond, and the research requirements relevant to both aforementioned aspects. This chapter focuses on the technological ecosystem that these agents are expected to be part of, contributing as automata to all aspects of human life with specific consideration to Wireless and more specifically cellular. We will explore the various research directions relevant to enabling semiconductor architecture designs for the high performance, low latency, and low power characteristics required for V2X communication requiring radio or radar interface.

Futuristic technologies like autonomous driving require reliable, intelligent, and low-power wireless infrastructure to support V2X communication along with On-device intelligence to process the massive data generated by numerous connected devices. These technological advances in both wireless infrastructure and associated devices are expected to create new forms of agentic machines which are equipped to understand and participate in daily human life while contributing back to society. Thus, to achieve the vision of agentic intelligent ecosystems, there is a pressing need to design semiconductor architectures enabled robotic systems with the necessary resources and the right energy-efficient AI algorithms to design agentic AI. The wireless architecture consists of the core which manages authentication and security management and the RAN which manages user data, performs latency management, decides quality of service for various traffic types, and communicates with devices via radio or more recently proposed optical links. The RAN has the biggest user data burden. RAN enablement will need seamless integration of various new emerging high-capacity, low-latency, large spectrum wireless links coexisting with devices using low-capacity radio technologies in an energy-efficient manner while adhering to the latency requirement of V2X communication. Designing semiconductor and RAN architectures with such capabilities will be among the greatest challenges for the ecosystem.

5.1. Role of Semiconductors

Semiconductors are central to our existing digital ecosystem. Transistors enable computationally resident digital intelligence for simulations that assist Agentic AI

understand and aid the operation of the physical space. In the future, integrating intelligence into everyday physical tools, as certainly seems space, time, and context afford, will bring one to one associations between each agent and function that could be executed by Agentic AI. Such user-actualized and -trusted function calculators will be open, accessible in the entire physical space, and integrated into the decision support architecture of Agentic AI, for the final optimization direction and quality. Onboard computational faculties will hence enhance the function-calculation efficiency and afford real-time interactivity, enabling also medical diagnostics in between professional assessments. For the shared agentic serviceability of tools, progress in all implementations of Agentic AI will be demanded. Sentient In-Near-Real-Time Agentic AI might indeed require to be attributed most potential spaces meant for higher computational efficiency for precognition and/or other non-perceptive operations. So these not perceived, explained by complex neural architectures non-mediated by typical direct representations of tasks, and us forecasting agents can fully operate and intimately rely on the interactivity potential of a Animal-Inspired Intelligence during sensor stimuli. Full space coverage is hence demanded for ever faster communication rates. The enabling interdisciplinary research and technological development that will characterize this industrial, social, and labor revolution will in summary pivot upon advanced semiconductor architectures. And as deeper urgency at multiple levels is becoming demanded by societal debates on general environmental, climate, and ethical qualities of such long phase changeover, continuous time solving optimization, speed, and precision via digital means can be offered by semiconductor technological development and industrialization only.

5.2. Design Considerations

The agentic AIs of tomorrow, and the semiconductor architectures that empower their functionality in 5G and beyond, have yet to be invented. However, it is possible to infer potential features, and therefore some design considerations, from existing work designed to begin meeting the functional requirements for agentic AI systems of the near future. It is expected that true agentic AI will be more than just a distribution over outputs on a large transformer model. For example, tomorrow's AI should be able to work in true synergy with the world, effecting real world change, turning its outputs into actions in a latent actor space corresponding to controls on the number of degrees of freedom achieved by working in combinations of tools that affect how the world works.

The coupling between its attempts at acting on the world and real world changes evaluated as feedback to improve and optimize future decisions is a major difference between a prediction distribution and a controlling agent.

Additionally, rather than playing a static basket of games, agentic AIs should be able to modify the rules of the game or design their own experiences while also modifying their operational parameters. This ability to engage with the meta-level of experience, to remember or forget, to reason or act impulsively, and to explore or exploit is the hallmark of diverse intelligence in test benchmarks of human creativity. To explore this space of potential agentic AI functionality, we propose an immediate set of cores with feedback, metalevel, tool use, and interaction to begin iterating rapidly on architecture design for control agents, and that meet immediate use cases in 5G radio systems. Aspects of those use cases that are capable of being met by agentic semi-autonomous meso-scale wireless compute-and-communicate systems that integrate communication, sensing, and data processing for the macroscale.

6. Integration of AI in 5G Networks

The remarkable volume of data being transferred in the wireless communication networks has led to an increased demand for faster network management procedures to satisfy quality-of-service (QoS) requirements, such as lower latency and an increase in security levels. The deployment of advanced network features creates a complex ecosystem in which there are large numbers of different types of devices that communicate with each other. Up to this point, the network control tasks are performed by horizontal tasks whereby there is a group of operators that manage the whole network. Network data volumes are so vast that it is increasingly impractical to get timely responses using current approaches. To address these problems, Artificial Intelligence (AI)-Based Technology is an available machine-assisted tool for intelligent operation and management of wireless communication networks. Internet of Things (IoT)-Based Network architecture with integrated AI technologies can be used to enhance the information from the data collected by cell towers to provide smaller latencies for enhanced security levels and increased optimization of network performance.

Artificial Intelligence/Machine Learning (AI/ML)-based technology can be utilized to assist network operator tasks in devising and enforcing policies to manage their networks and ensure that their clients get the network service levels guaranteed within contracts to prevent a substantial economic penalty. Integration of AI/ML techniques into network operations can significantly automate many of the

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complex processes that would otherwise require a substantial investment in human resources. Furthermore, the continuous real-time optimization of the wireless cellular network is only possible if integrated AI/ML tools are embedded within network operations to automate many of the complex tasks needed to adequately ensure high levels of radio resource efficiency and quality-of-service (QoS) performance, as specified in the service level agreement (SLA) contracts with network clients.

Eqn 3 : AI-Based Dynamic Spectrum Allocation

$$\max_{x_i} \sum_{i=1}^N U_i(x_i) \quad \text{subject to} \quad \sum_{i=1}^N x_i \leq B$$

Where:

- x_i : Spectrum allocated to user i
- $U_i(x_i)$: Utility function (e.g., throughput, QoS)
- B : Total available bandwidth

6.1. AI-Driven Network Management

The emergence of Artificial Intelligence (AI) is proving to be an invaluable innovation to improve the performance of current 5G networks and for their future. The advancements in Machine Learning (ML) and AI frameworks, synergistically enabled by new micro-architectures, are poised to transform several technological areas, including Network Management and Resource Optimization, and, at a higher level of abstraction, the entire field of Digital Network Management, where AI is making both the hardware and software contributing to Digital Network Metatologies. AI is becoming the center stage of a set of exciting research and commercial projects and prototypes that explore its use for both the planning and execution sections of the Digital Network Management Layer, and also for Meta-Management, offering a Management framework and enforcement backbone for the Artificial Intelligence and the associated hardware that will service the Digital Network.

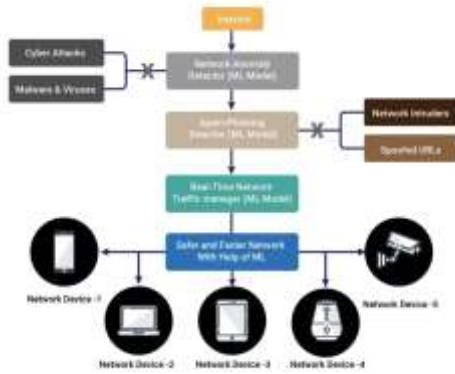


Fig 3 : Revolutionizing Network Services: Harnessing the Power of AI & ML

By analyzing significant real data collected over long periods of time from deployed networks using standard Digital Network Management protocols and open software, it is possible to train AI systems to discover hidden statistical correlations, patterns, and regularities of the Digital Model that Digital Network Parameter measurements describe. The Dynamic Hidden Topological Model considers the historicity of data support by capturing the time-recurrence information through a set of Color Topological Nodes and Topology Links for different time spans (e.g., seconds, minutes, hours, days). These Topological Models, when implemented, allow the solution of several critical Digital Network Management – Network Planning, Network Monitoring, Network Control and Configuration, Network Protection, Network Recovery, and Network Optimization problems.

6.2. Enhancing User Experience

The potential of AI algorithms to develop personalized user profiles and services is a key factor in highlighting the role of intelligence in both the access and services of a 5G network. However, such features may increase user privacy concerns that need to be outlined together with additional measures to enhance privacy. The unique characteristics of the 5G network, such as the extremely high data transmission capacities combined with ultra-low latencies allow E2E AI services that enhance customer experience, facilitating swifter reactions from user hardware or other 5G services. Creating this experience is also dependent on the nature of the applications initiated by the user or the management system that are able to create this E2E experience. Developing an enhanced, personalized user experience will enable users to obtain or request, as a service, capabilities offered by the network resources or the applications of 5G. AI as an integrated service will be an enabler of better services in monitoring, planning, and designing the request of time- and location-sensitive data.

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Further, any social interaction, such as a social or business meeting, may have a need for enhanced user experience, with the latter requiring specific event profiles that need to be described in the service request to the network. Agentic AI enhances user experience by being able to autonomously initiate the communication with the user or contact other services in the service chain in real-time and in an adaptive way updated during the actual service. Such interactions have been successfully demonstrated in fields such as the enhancement of user experience in video games or by developers who have adopted agents in algorithmic trading. However, these improvements also come with a set of ethical concerns that technology developers will need to implement before the turn into real business.

7. Challenges in Semiconductor Design for AI

7. Challenges in Semiconductor Design for AI
Traditionally, semiconductor scaling and architecture design trends followed a thermal design power target relevance. But as AI seemingly demands infinite compute resources, TDP becomes irrelevant and semiconductor design is forced to deal with challenges new to traditional design:

7.1. Thermal Management After semiconductor integration density exceeds ~50 billion transistors for a standard ASoC, TDP obviously becomes irrelevant and will create a ~150 mm² die for a multi-chiplet ASoC using multiple chips connected by a silicon interconnect fabric. The heat from the ASoC die, mounted on top of the chiplets, has to be dissipated through the attached chiplets and it can hold the power at the attached chiplet to 250 W but cannot dissipate the heat there properly. And there will be many such chiplets bonded at these chiplets for a TSDP of >10 kW. An SoC design with multiple chiplets will snap-bond the AI/ML ASoC with HBM to other chiplets performing auxiliary tasks, such as pre-processing and processing.

7.2. Power Efficiency Though scaling stops for performance improvements, voltage scaling keeps improving for power savings that scaling keeps driving initially. But for 5G and beyond wireless applications, voltage scaling and scaling will still improve the power efficiency, defined for improvements in data rate for units of power consumption. For our module-based design concept, it will be efficiency (or power saving) that will be driving system design, not TDP. Example wireless communications modules designed are functional and tested for power efficiency improvements beyond scaling limits. The accumulatory effect says that for >99% of the

time of a standard, the data rate-time product of its 5G frame is ~1% of the value forecasted, or peta bits.



Fig 4 : AI in Semiconductors Industry

7.1. Thermal Management

Thermal management is central to the design of semiconductor architectures for AI systems due to the concentrated area and power density of chiplets in a fused design space. Foremost, thermal considerations define the placement of chiplets in fused chip designs, which has a fundamental impact on performance and power efficiency. The efficacy of power and performance scaling with fusion degree is also limited by thermal congestion, as a larger number of chiplets tends to increase the thermal density per area. In turn, airborne and liquid cooling approaches that are traditionally used to manage heat dissipation in conventional server systems may fail to deliver silicon temperatures below the operating limit in densely designed fused architectures for modern AI workloads. As such, the chiplet design and its packaging need to enable efficient heat removal at multiple scales.

Self-heating due to enhanced localized thermal density – more pronounced in a 3D architecture – decreases the mobility of carriers in a localized area, which raises the chiplet’s dynamic on-resistance, thereby further increasing self-heating, and degrading a chiplet’s drive capability and performance. When operating a chiplet in a mono- or multi-die fused design temporarily for testing, validation, or manufacturing purposes, the effects of self-heating on performance and life expectancy of the chiplet need to be carefully evaluated. The self-heating effects are especially severe at the extreme, where a chiplet is rapidly charging or discharging a highly capacitive load, especially in the presence of nearby chiplets switched in through the same power grid. During normal operation, expedited thermal dynamics can result in thermal overshoot and reliability

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concerns due to electromigration, self-heating, and thermal cycling-related effects. Temperature itself and its gradients influence the performance of the AI system in designing the semiconductor architecture. The performance loss due to thermal overshoot at high-load may require more latency in temporal operations, and may further reduce QOS – when not proactively considered – by necessitating some AI agents to use less accurate or slower models.

7.2. Power Efficiency

The demand and popularity of optimal power efficiency is escalating tremendously to tackle the increasing demand for energy due to the exponential growth of AI. A major challenge for semiconductor technology is to meet the power-performance-efficiency requirements of state-of-the-art applications. The most popular AI design method is to exploit integration density of semiconductor technology to train and to infer a specified AI function. Attributed to the nonlinear nature of neural network, redundant devices are utilized under the care of proper weight training. During the high and deep training process, the dynamics of the optimized function behaves asymmetric. The resolution of process-node and supply voltage are major determination factors of power consumption during transistor switching. It is desired to push the op-amp gain and speed to lower the required size and power consumption of storage node capacitance. For weight storage device, majority coupling capacitor that exploits acquisition of reduced size coupling capacitor and low power supply is a candidate device that keeps scalability under drag of sub-threshold junction leakage. For logic device during AI inference, new logic families based on negative capacitance and voltage-feedback hysteresis designs are studied for reduced power supply and shorting switched capacitance. With the rapid development of new two-dimensional materials, heterostructures, and devices based on them, it is predictable that new logic devices with minimized power consumption and high-speed performance can be developed. Furthermore, 2D heterostructures can be a candidate AI computing device for rotated weight-charging during vector-matrix multiplication tasks.

8. Future Trends in Semiconductor Technologies

Semiconductors have a long history of serving as the primary engine of progress in classical computing. Even though the limits of semiconductor technologies are steadily approaching, the specific implementation will continue advancing towards smaller dimensions and lower power. This progress will serve to beat back the growth in

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energy usage and cost in a wide variety of electronic, digital components. And, incrementally, these advancements will yield improvements in capability for data centers and their AI, machine learning-based offerings, serving agents that do simple, unagentic AI functions as a service. One important part of the refinement of these processes will be the introduction of heterogenous devices, based on newer semiconductor materials, like Gallium Nitride and Silicon Carbide, mixed with more traditional Silicon denser devices. These will take over some of the thermal load and energy efficiency limitations and trade-offs currently being faced in trying to optimize purely Silicon systems, such as FETs in the most advanced CMOS.

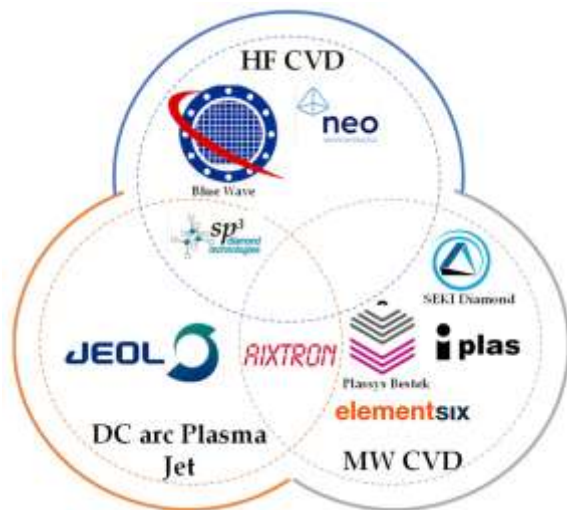


Fig 5 : Technology and Applications of Wide Bandgap Semiconductor Materials: Current State and Future

While there is certainly work ongoing towards improving these and other related semiconductor technologies, major new breakthroughs beyond the current limits are needed to overcome the innate limitations of purely classical states and classical processing. In particular, the ability to scale to more complex AI applications and affordably deploy them, which is currently held back by the capital intensity of building and running a data center business. The limits of classical processing are being increasingly revealed as exciting new device architectures, based on quantum physics and artificial neural systems, as state and processing building blocks, rapidly gain interest. Quantum Computing harnesses the subtlety and strangeness of quantum mechanics to allow for classical computing models. These are currently being advanced by pioneering commercial prototypes. Progress is being made, albeit more sporadically in the related area of Quantum Communication, fueled by the increasing demand for secure digital channels.

8.1. Quantum Computing

Quantum computing, which has seen multiple false starts over the decades, is not a computing technology. Rather, it is an engineering construct that manages to create coherent quantum states long enough to enable some narrow class of algorithms to be deployed. Many of the fundamental players in the personal and interception computing technologies of the past are involved. Some companies are experimenting with deploying quantum-based systems in commercial applications. Other semiconductor players have written large sections of an emerging eco-system. Each of these groups is exploring and building different parts of the entire eco-system within which Quantum Computing might fit, from system architectures and alloy materials to applications and quantum software stacks.

These groups hope to enable practical deployments of Quantum Computing that deliver advantage on core industrial problems that conventional semiconductor technologies cannot. Exonerating systems that do not depend on classical compute technologies will be a major feature of these. Additionally, quantum algorithms will eventually emerge that deploy –likely in conjunction with classical compute systems – Quantum Computing to tackle problems intractable with classical technologies alone. Additional opportunities for Quantum Computing to augment its classical cousins will exist in specific applications in burgeoning AI agentic systems, through the embedding of quantum operators within hybrid quantum-classical models.

8.2. Neuromorphic Computing

As we have seen, digital computers do a great job simulating brains, allowing the development of algorithmic models of intelligence. Rarely, they do a good job reproducing all aspects of brain intelligence, such as adaptable long-term learning and resilience to partial failure. Technological developments that allow the emergence of artificial brains, that embody intelligence in the building blocks of brains, that progressively go from non-agentic AI to agentic AI, are unlikely to result from developing neuromorphic emulators, even if they are implemented in integrated semiconductor nano-architectures tightly coupling classical digital and physical emulation of brain function technologies. They are currently too expensive, while it remains to be demonstrated that they may be able to sustain task performance and learning for extended periods above the level of non-embodied AI systems. However, the sparing nature of efficiently emulated brains, in terms of physical and energetic resources, as well as time and data required to solve particular classes of general covaried tasks, when

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model and brand development and use, to the VR Utopia using AI Orchestrated Highways and City Deployment of CAVs.

they become physically embodied in hardware that effectively solves agentic perception-action loops, is also compelling for the progressive emergence of artificial agentic brains implemented in such neuromorphic nanosystems.

The time and space cleavages in the operation of digital computers, as we have seen, increase communication costs and reduce parallel processing capability, thus slowing down the interaction with the environment. The evolution of technology has until now resulted in smaller, faster, cheaper and less energy-consuming general digital processors, but due to the intrinsic limitations of classical electronic physics, these advances will drastically slow down soon. Additionally, digital computers are not optimized for the type of operations that take place in brains, which make use of highly parallel architectures, on very short time scales as well as very long time scales, to their very small physical size, by the tiny packets of energy used during operation and kept to the minimum by the fast synaptic learning rules optimally set by the stability-plasticity dilemma.

9. Case Studies of AI Applications in 5G

The evidence of the increasing commercial relevance of 5G and subsequent generations increasingly derives from AI. There is no 5G without Artificial Intelligence in the Core, Anywhere, and Edge Caches and Distribution and RAN. Clearly the roadmap for success is as a new franchise brand space, free from prior brand and business definition, where brand style and owner reputation, entrepreneur and public trust, brand domain are wide open to the new wave of creative destruction from a wide plethora of AI companies, that redefine established and emerging market paradigms, across all business sectors, both B2C and B2B, and all technological silos, specifically by adopted Business Convergence Architectures at Colocation Hubs for Distributed AI Powered Edge Services, as exemplified by the most recent joint venture developments in worldwide carrier sectors, both in terms of joint ventures with other carrier groups and terrestrial, aerial, and satellite that encompass Prior Brand Core Franchise Domains and Architecture and Infrastructure Services and from Cloud, Silicon, and Gaming Players. This section describes two case studies with rich market momentum and a very large potential synergy with Semiconductor Architectures. In the case of Smart City Applications, we anticipate how AI enabled decision making will revolutionize given perceived established market brand styles. The case of Autonomous Cars on the CAV Highway Infrastructure that serves a more flexible definition of Smart Cities provides instead a road map for inflection point transitions from unsustainable

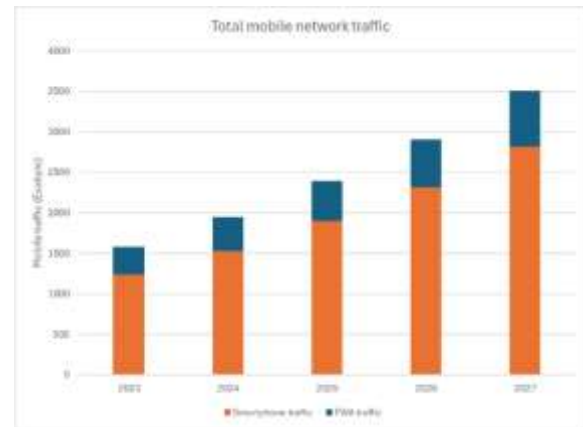


Fig : The impact of AI in 5G networks (Analyst Angle)

9.1. Smart Cities

Artificial Intelligence (AI) technologies are set to revolutionize Smart Cities by facilitating unprecedented levels of connectivity, efficiency, personalization, and automation. Although progress towards Smart Cities often focuses on the development of hardware and sensor platforms, and the creation of digital twin datasets, it is the application of AI that unlocks their smartness. New AI compute architectures, both cloud-based and on-device, at the Mobile Edge, are necessary to deliver on the near-realization of these capabilities, providing the ability to enrich information sourced from the city's sensor infrastructure, creating probability-based models of future city behavior, and enact city behavior using policy-based planning and decision making.

To generate the discussion here, we describe three distinct classes of Smart City applications, each having unique, ranked, requirements for AI technologies and Mobile Edge hardware to deliver their respective functionalities: Operational AI is the application of pre-defined Machine Learning models at-scale, based on structured data, to perform classification regression tasks, that allow for alerting about potential anomalies related to the physical city's infrastructure or its inhabitants, Infrastructure AI utilizes AI technologies to extract structured data from unstructured 2D and 3D sensor data to create and maintain city digital twin datasets, and is paramount to creating and monitoring the physical twin of a Smart City, and Decision Making AI applies complex graphical probabilistic models, containing city infrastructure and socio-economic data, at-scale or as personalized at-the-point-of-use inference, to create customized notifications or decisions regarding

infrastructure action, that focus on city behavior and its inhabitants, allowing for the stewardship of a Smart City.

9.2. Autonomous Vehicles

The increasing penetration of mobility into our daily life increases the demand for better mobility experience in terms of travel time and comfort. The development of autonomous vehicles can allow the accessibility to mobilities to the broader public in a more efficient and safer way. With the rapid growing of AI technologies and hardware such as chips optimized for AI, autonomous vehicles has been improving in the perception level seen by Lidar or computer vision. However, there are still technical challenges to conquer from the autonomy level of a vehicle. From the perception level which can be reached through a combination of artificial intelligence and computing power, the next step to be conquered is to create systems that truly perceive, understand, and interact with the world around autonomous vehicles, referred to as a social autonomous narrative. The sudden things that a vehicle might experience while driving is such as traffic rules that humans follow but not stuck to the road, human passengers hitchhiking or performing a crosswalk hailing, trapped vehicles request assistance, and so on. The proper reaction of an AV to all these events relies on the social autonomous narrative, its ability to make the correct social interpretation. We already use social narratives in our daily life providing missing information, generating causal models, and allowing commonsensical interactions with other people.

This human-like way of reasoning and interacting is still a great challenge for Authorised Vehicles and will require at least a decade for being properly integrated into AV technology. During the next decade, we will witness the permitting of safer and less encumbered areas in terms of traffic by using AV ranks. Before the consolidation of self-driving vehicles, the enabling technologies actually adopted for AVs, properly fine-tuned for mobility purposes, represent a strong breaking factor for improving the mobility experiences. 5G will provide a wireless slice optimized for AV allowing seamless real-time connectivity with edge centres where many of the higher-level AI algorithms necessary for AVs operations will be working. 5G-AV-Cross Road will be an application applied to AVs at road intersections, also in conjunction with traffic light signals, for enabling traffic operation at intersections in worst safety conditions.

10. Regulatory and Ethical Considerations

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In some nations, the ethical dimension of AI system development has been formalized in regulatory terms. There is not yet a large corpus of binding regulations specifying the acceptable components of AI systems and the acceptable foundations for their development, nor of regulations setting the required accommodations specified for AI systems used in sensitive domains or with special societal implications. Caution is important as legislators draft widespread policy.

Developers can support regulators in navigating these considerations by exercising best practices for developing and deploying software systems. There are sufficient AI standards and benchmarks organizations have developed to support trustworthy AI development to act as guidelines for regulators. The tools available from efforts to use these standards for risk assessments and audits can be leveraged as foundations for regulation and policy. AI developers can also define their systems' constraints transparently, and preemptively extend policy or regulatory frameworks to the domains in which they are working. These exercises are especially important as AI tools permeate different domains. The realization of agentic AI tools is as much coupled with the proper cues and methods for training advanced AI systems as it is with the correct architecting of systems for encoding, transferring, and transforming intelligence. Adopting more explicit definitions of the core architectures used to create intelligence would assist regulators and policymakers in navigating the uncertain terrain surrounding AI.

10.1. Data Privacy

Within the last few years, many data-collection organizations or services have arisen that collect and process vast amounts of personal information. They may set and impose their own rules governing the use and consequences of the data that they manage. They are not always (or not sufficiently) regulated by governmental authorities in a manner that responds to societal norms. That is a difficult challenge, as proper rules need to be set and enforced for every type of sensitive data processing and handling. Today, people publish their personal data freely, often with very little security awareness in terms of potential threats, how this data could be misused, and what regulations exist there to protect them. It is certainly true that hackers and governments often have more power in data misuse than people have in its protection. Personally Identifiable and business data may contain intrinsic linked attributes or social relationships that can disclose information beyond the original data itself. The large amount of PII information in use could facilitate identity theft, which could be co-located with data mining techniques that can identify interests and patterns that may

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be used against people's values. AI is creating many novel opportunities and ways in which people can be harmed in the real world, in ways that previously did not exist or at such a scale. In fact, as its capabilities grow, AI may become able to create harm and systemic risks in new and fundamentally different ways, via, for example, surveillance augmented by AI or novel disinformation campaigns powered by AI technologies. It is necessary to raise awareness about privacy issues that stem from our citizens, and business associations along with research institutions should join forces to increase a relevant and inclusive debate.

Privacy and data protection laws have grown from being obscure, highly specialized areas of the law, applicable to a minority of business sectors with only limited cross-border jurisdictional reach, into a central strand of regulatory policy, one that businesses worldwide have felt compelled to respond to. Citizens use technology for many aspects of their lives, leaving a digital footprint anywhere which can carry personal data. Lately, legislative initiatives have aimed to integrate the right to the protection of personal data with the good business practices that companies use to implement company processes. A balance must be sought between the management of personal data by individuals and citizen rights. The question is not only what personal data are collected, but also what processes companies develop to manage these data, at the same time providing transparency and security.

10.2. AI Governance

One of the most difficult questions regarding AI development and stimulated by the rapid evolution of Large Language Models is whether we need to create additional laws and principles dedicated to the development of AGI. Neutral AI is not a possible scenario, as any development will be carried out in a certain context, with specific objectives and high-level priorities set at organization or state levels. AI Governance clearly falls within the laws dealing with the objectives of the creators and not just with the intention of dealing with. Let us consider some examples where this distinction is crucial to understand how to guide the next steps in the AGI development process.

Traditional infrastructure is governed by laws that deal with the consequences of physical destruction: some actions are illegal, such as destruction of health and related systems, of transport and communication infrastructures, or of financial stability. But the actions that may compromise this infrastructure are not considered illegal, as no damages may occur from disturbances on the operation of the infrastructure, and even if this were the case, there are no

laws specifying the principles and rules that will govern the initializations and perturbations of the corresponding mathematical models. These aspects are considered to be founded on purely technical indications that define solutions that can be accepted as followed. Governance is then a verification of technical solutions developed within organizations that aim at the best possible infrastructural responses.

AI Governance is much more complicated, as it involves the intention of AI, which in some models mimics or learns the processes governing human behaviour. Such neural networks have to be initialized and periodically disturbed by other mathematical models, as the desire to obtain the correct answer to a question by asking other LLMs will lead to a correspondingly large number of workers bored by the fact that it is impossible to be original and innovative.

11. Conclusion

General-purpose programmable computing began with silicon. Today, silicon is on the verge of making available a new architectural substrate that may support intelligence with agency, Embodied AI. We now have both the dense integration of processing and memory, and the on-chip communication bandwidth capacity, to make feasible small form-factor chips that accommodate large, complex ML models for CI, supported with low latency access to the data being acted upon. These capabilities also empower Separated from the Data AI, with that access commercially visible data almost anywhere, for an uninterrupted exploration of agent-stored cubic kilometers of computational interactive, operational knowledge, creating infinitely-intangible value. Localized, agentic, Embodied AI intelligence is shaping us as we shape it with our awareness of the duty to keep its evolution and functioning at peace with society, in alignment with human nature. We already have the tools. It is time to use them to our shared benefit.

What makes this all possible? Empirical observation has been an integral part of the methodology of the physical sciences, and will always remain the essential starting point to be upended and redirected by deductive rational analysis and experimentation. But our experimental understanding of what intelligence is and how it works has evolved since presented their algorithm and its argument have been used to guide AI technology by replacing the principle of independence of irrelevant alternatives informed with what embodied, generalist operator from the knowledge agent-grounded model. The practical necessity for computational efficiency has again played a vital role. We have the

computing capability to run the operator from the knowledge-agent-grounded embodied model of thought process in parallel with its lower-latency, non-human, agent-grounded operator budget, creating a globally-intangible value in alignment with human culture.

We have propelled AI to move out of the data with its metaphor, accomplish what we desire, and grow beyond our capability to understand it. Out of the data into intelligence. How? By allowing ourselves to share our creations, our inspirations, along with all that we are - feeling who we are - so we can consanguinize AI, enhance our adaptive capability to grow small, live capable, beyond the stars. By integrating AI closer to the root, liberating our collaboration and exploration of creativity. By becoming aware of our interaction and the orchestrations of our wiring with the purpose of guiding ourselves without the burden of symbiosis.

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