Electronic Design

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Engineering Trust Through Physical Intelligence in Humanoids

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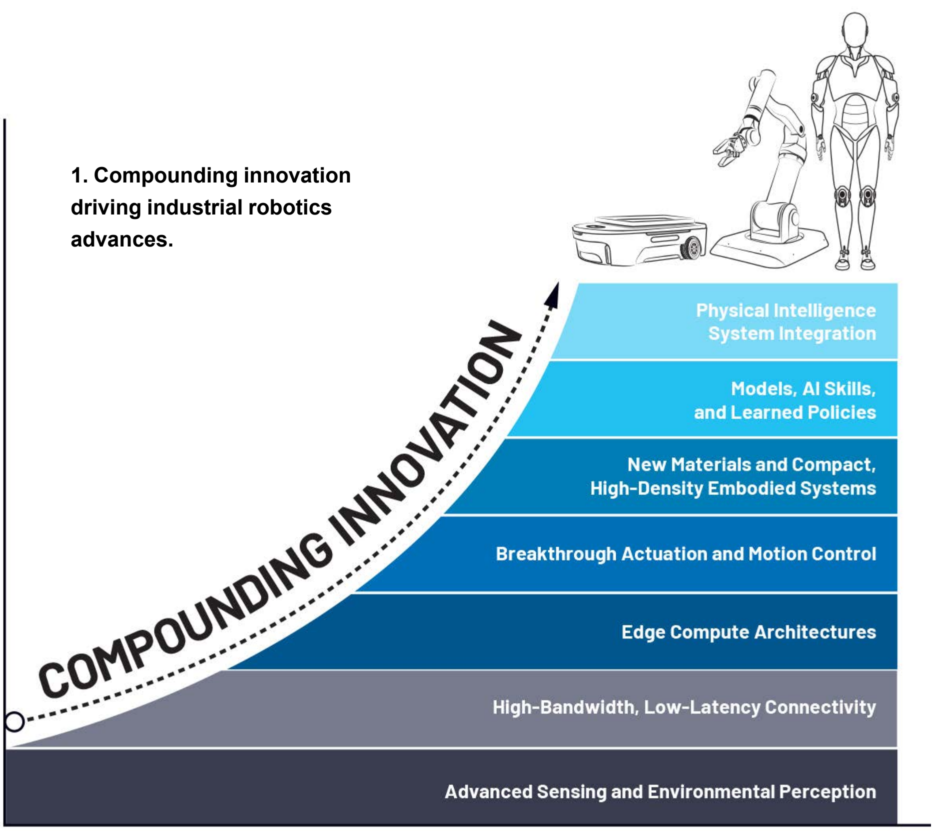
Locomotion enables access and dexterity adds capability, but scaling humanoids depends on both data and trust. Data powers the AI models, learned policies, and sensor-fusion systems that expand autonomy; trust comes from ensuring those systems behave reliably in the physical world.

That's the role of physical intelligence: AI reasoning aligned with physical constraints and enabled by continuous sensing, deterministic connectivity, real-time control, and responses bounded by the laws of physics.

Humanoid robotics represents a turning point, not because intelligence has improved in isolation, but because innovation is converging across sensing, deterministic connectivity, compute, motion, power, simulation, and safety, all inside the physical control loop. The modern humanoid era isn't enabled by AI or hardware alone. It's also enabled by the compounding interaction of these domains, grounded by physical signals, and adhering to real-time constraints.

This compounding effect is transforming robots from rigid automation into physically intelligent systems.



1. Compounding innovation driving industrial robotics advances.

From Automation to Physical Intelligence

Traditional industrial robots were designed for predictability. They operated in structured cells, executed preprogrammed routines, and relied on separation (cages, light curtains, and strict zoning) to manage risk. Humanoid robots push beyond that model. They must function in open, dynamic environments, share and navigate spaces with people, and respond continuously to unexpected events.

In these conditions, intelligence must be continuous, time bound, and embodied. The result is a new class of systems that don't just execute preprogrammed steps, but operate with physical intelligence:

- Sensing what's happening
- Deciding how to respond
- Acting on the environment
- Observing the result
- Adjusting immediately

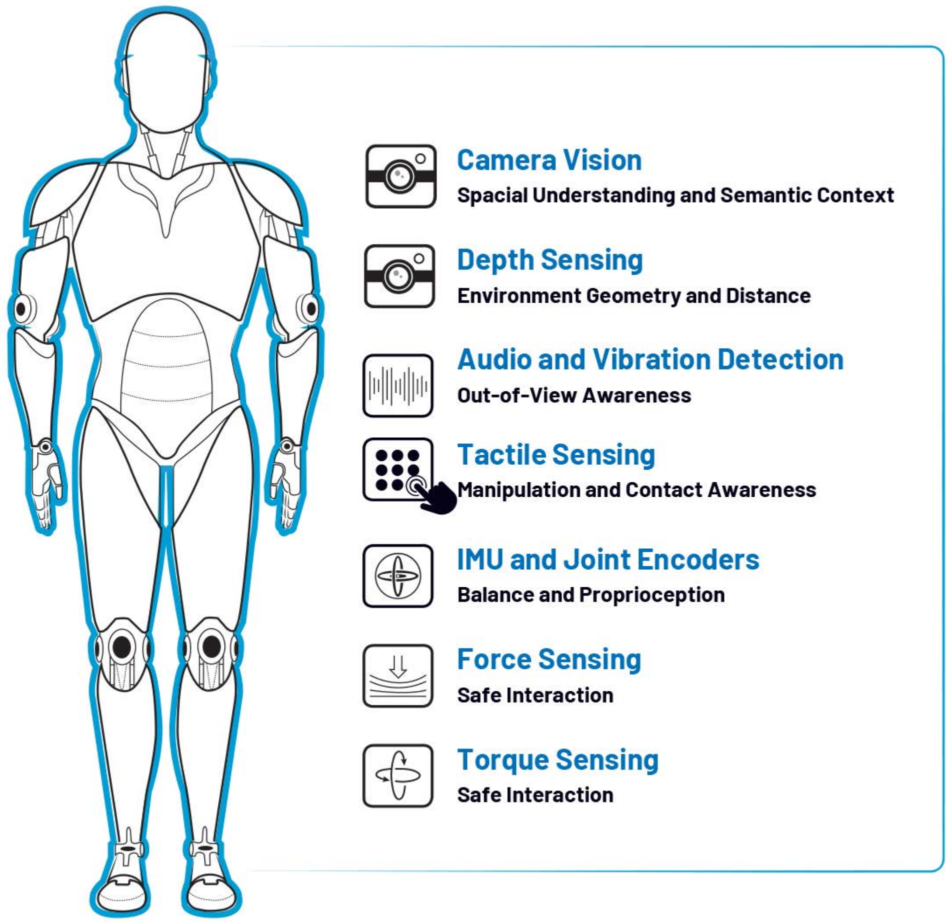
In the physical world, this loop is the minimum requirement for stability, safety, and useful work. In physical systems, there's no pause between steps — latency, jitter, and missed updates show up as visible behavior such as hesitation, oscillation, or hard stops. Time doesn't stop, and intelligence must move in lockstep with it.

When this loop is well coordinated, robots move smoothly, handle uncertainty, and collaborate naturally with people. When it breaks down, the failure is rarely subtle *(Fig. 1)*.

This is why physical intelligence is fundamentally a systems engineering problem. It requires tight alignment between AI models and algorithms, perception, decision-making, and control. The result is a tightly orchestrated, time-synchronized system.

Multimodal Perception

Humans don't rely on a single sense. We continuously integrate vision, sound, touch, balance, proprioception, and force feedback to understand the world while moving through it.



2. Multimodal perception as the data substrate for physical intelligence.

Humanoids operating in real environments must do the same, but with an added requirement: Their perception must be structured so that AI can reason about physical reality, not merely classify what appears in a scene. A humanoid perceives, interprets, and reacts through a continuous flow of information moving across its body between sensors, compute nodes, and actuators at precisely the right time *(Fig. 2)*.

Modern humanoids increasingly fuse:

- **Vision** for spatial understanding and semantic context
- **Depth sensing** for geometry and distance
- **Audio and vibration** for intent, environmental context, and out-of-view awareness
- **Tactile sensing** for manipulation, contact awareness, and grasp stability
- **Inertial measurement units (IMUs) and joint encoders** for balance, orientation, and proprioception
- **Force and torque sensing** for safe interaction, load estimation, and physical constraint enforcement

Together, these modalities enable robust perception under motion, glare, occlusion, clutter, noise, and uncertainty. A humanoid can't act intelligently until it's able to perceive intelligently — continuously and in context.

Deterministic Connectivity

Perception generates data. Connectivity moves and synchronizes that data. Rather than monolithic machines, humanoid architectures are increasingly built as distributed, interconnected networks. Multimodal data insight depends not only on what each modality measures, but when it was measured.

Preserving time coherence across sensor signals allows AI to reason about cause, contact, motion, and consequence. Camera zones, sensing zones, and actuation zones connect through hierarchical links, from modest data-rate edge buses (1 to 10 Mb) to high-speed backbones (2 to 10 Gb) *(Fig. 3)*.

With deterministic connectivity, robots gain a unified sense of self and surroundings, enabling smoother locomotion, safer collaboration, adaptive manipulation, and consistent behavior under uncertainty. Without it, distributed intelligence collapses.

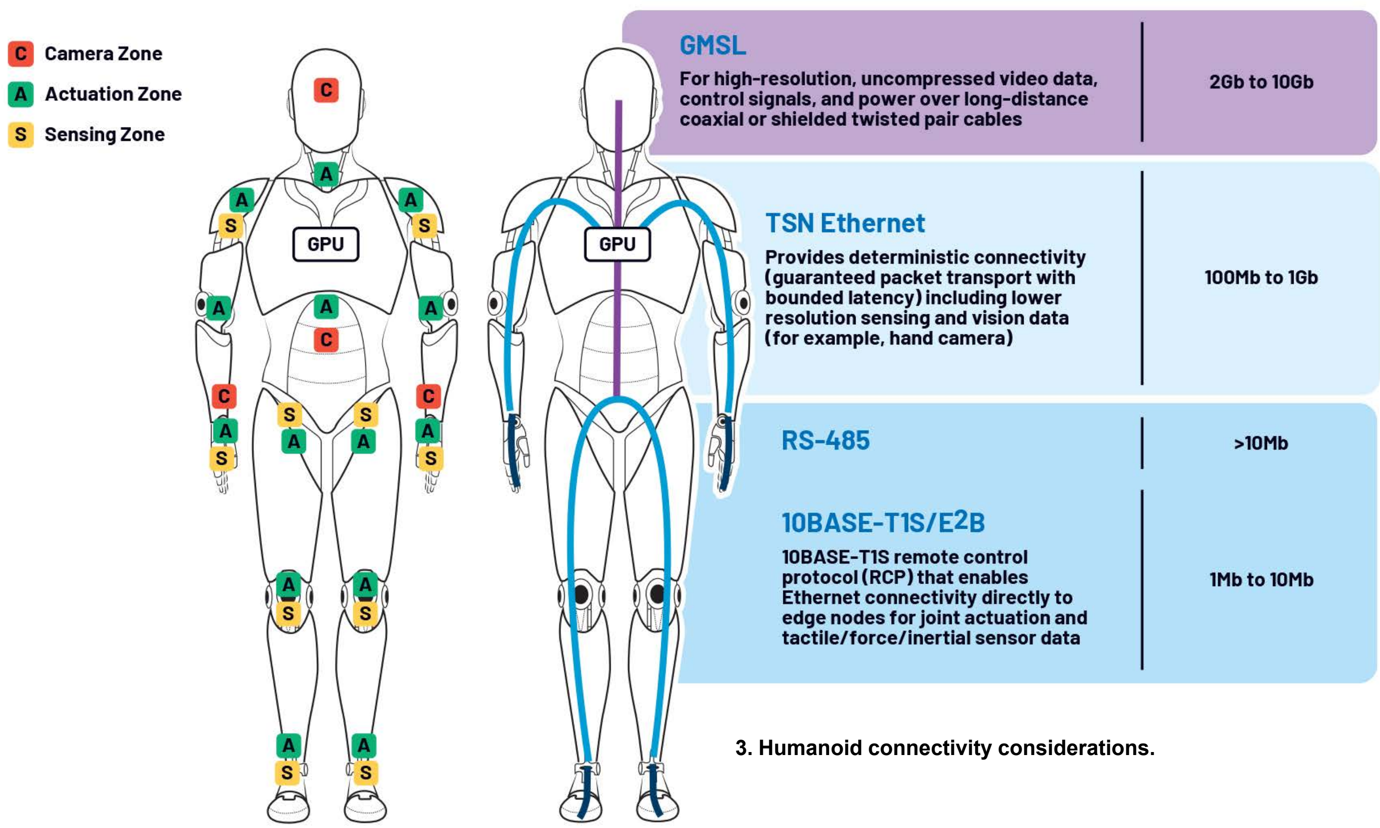
Three Layers of Intelligence

Popularized by Daniel Kahneman's book, *Thinking Fast and Slow*, the System 1/System 2 distinction describes fast, intuitive response and slower, deliberative reasoning. For humanoids, that framing needs a physical foundation: System 0, the real-time nervous system of sensors. Humanoid performance depends on these systems operating together as a synchronized loop from touch to thought to torque.

Consider a humanoid carrying a partially filled open container down a busy industrial aisle. What appears simple spans multiple system domains:

- **System 0—Physical signal and actuation substrate, sub-5-ms class:** sensors, actuators, joint state, motor currents, tactile signals, IMU updates, and low-latency local loops.
- **System 1—Fast interpretation and reflexive response, 5- to 20=ms class:** sensor fusion, slip response, balance correction, force adjustment, local motion control, contact modeling, and safety enforcement.
- **System 2—Cognitive reasoning and task planning, ≥50-ms class:** route selection, human motion and intent prediction, task intent, policy-level orchestration, and planning.

Physical intelligence emerges from the coordination of these layers: System 0 grounds the robot in real physical signals; System 1 converts those signals into fast corrective behavior; System 2 reasons over task goals and environmental context. The robot succeeds only when sensing, reasoning, and action remain synchronized.



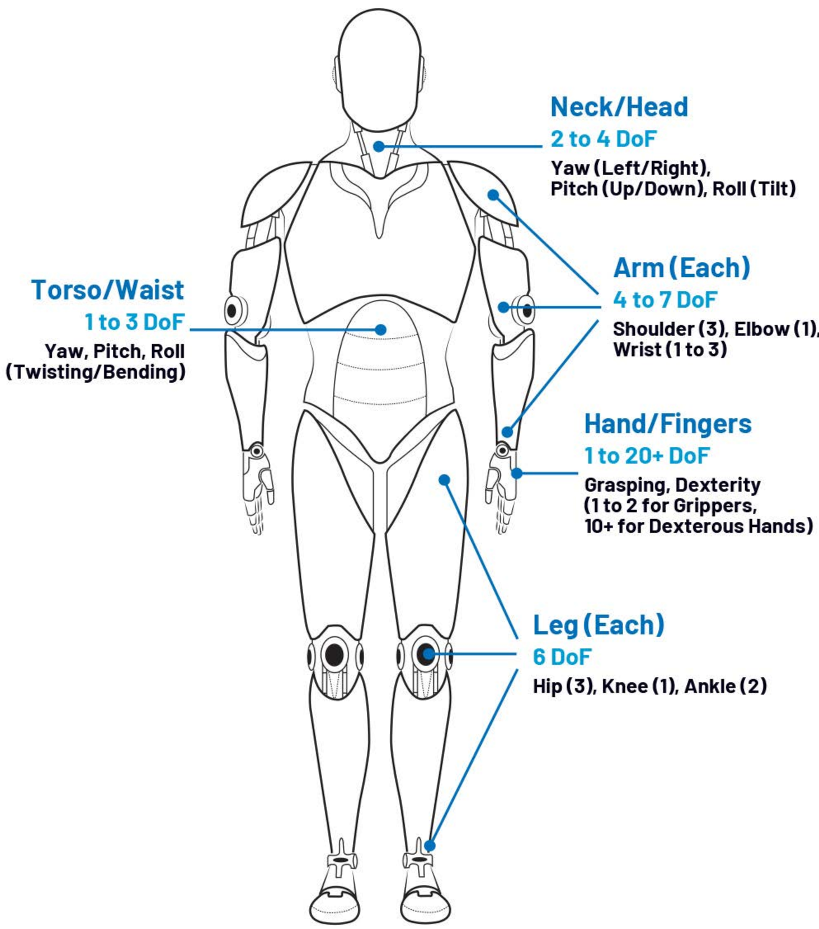
3. Humanoid connectivity considerations.

Real-Time Motor Control

Humanoids are often judged by how they move: steps that settle cleanly, reaches that adapt mid-motion, balance corrections that occur without visible hesitation. These behaviors are produced by coordinated control across dozens of interacting degrees of freedom (DoF) *(Fig. 4)*.

As DoF increases, capability scales and so does control complexity. Each joint adds coupling, reduces latency margin, and introduces additional paths for instability. Small timing errors propagate rapidly. For example, a delayed ankle correction alters knee loading; a wrist disturbance shifts shoulder torque; a torso adjustment redistributes balance across the whole body.

Real-time motor control is therefore foundational. Coordinating many DoF requires continuous, reliable joint state awareness across position, motion, and load — all maintained through power interruptions, dynamic forces, and mechanical wear. Whether using rotary actuators with gear reduction or linear actuators driven by lead or ball screws, motion quality depends on high-fidelity position sensing, low-noise signal chains, and predictable timing at the actuator level.



4. Humanoid motor control: DoF challenges.

When sensing, motor drive, power, and control are engineered as a coherent system, motion scales without collapsing under timing uncertainty. Complexity doesn't disappear; it's managed deterministically. Digital intent becomes physical behavior only when signal integrity and timing are preserved across every joint, every cycle, and every physical interaction.

Functional Safety

Humanoids become transformative when they can work near people. That shift from fenced automation to shared environments redefines safety. Mechanical compliance and back-drivability reduce injury risk, but they're not sufficient. A robot can be mechanically soft and still unsafe if sensing is wrong, timing is nondeterministic, or faults fail silently.

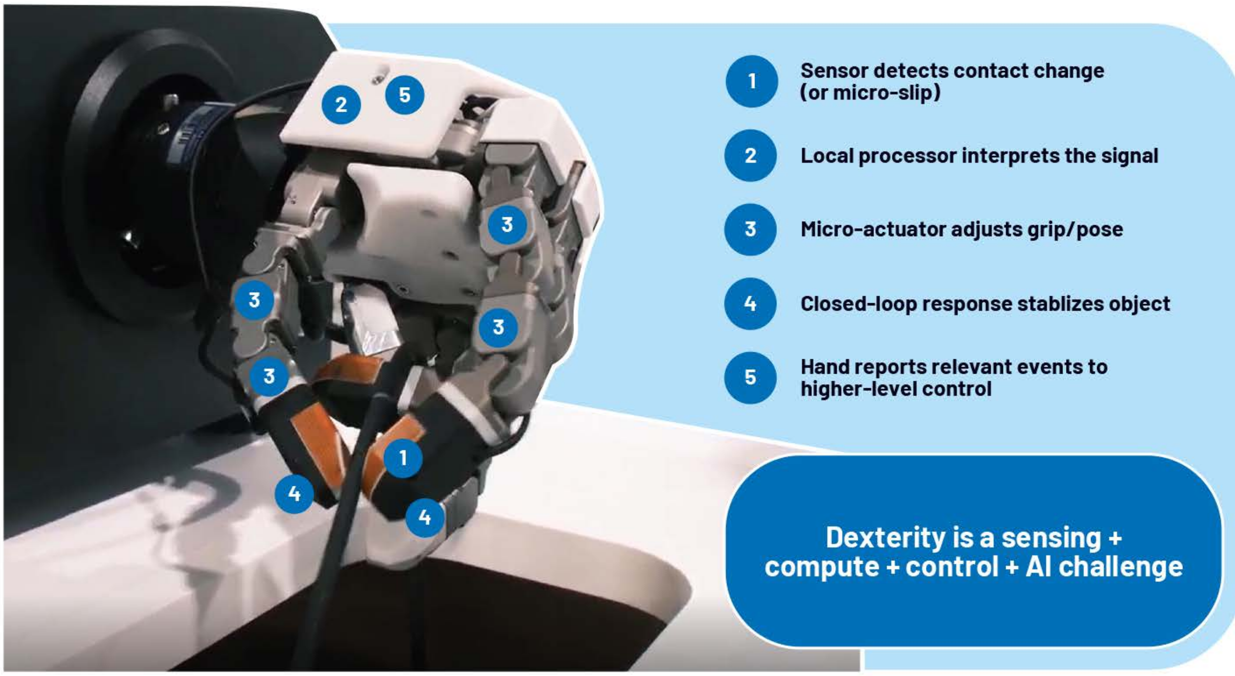
Functional safety in human proximity requires multilayered protection:

- Bounded limits on force, torque, speed, and workspace
- Continuous diagnostics, sensor calibration, and plausibility checking
- Redundant sensing and diverse safety paths
- Deterministic response under fault conditions
- Controlled degradation instead of chaotic failure

Because humanoids are coupled systems, safety can't be confined to one module. It must span perception, connectivity, compute, power, and actuation, end-to-end. Predictable behavior under fault is the difference between impressive demonstrations and scalable deployment. Trust is earned not when everything works perfectly, but when the unexpected happens and the system responds safely, consistently, and transparently.

The Humanoid Hand: Where AI, Sensing, and Control Become Physical Intelligence

Nowhere are system demands more compressed than in the hand, where sensing, actuation, wiring, and reflex-level



5. Dexterous humanoid hand manipulation.

control converge under the tightest latency, power, thermal, and size constraints.

Humans modulate grip force without thinking, sense slipping before an object falls, adjust contact pressure as surfaces change, and reposition objects mid-motion with tiny corrections that never rise to conscious attention. Replicating even a subset of these capabilities in humanoid hands demands breakthroughs across high-density tactile sensing, precision motion control, compact actuation, low-latency local compute, learned policies grounded in multimodal sensing, and robust power management — all inside a lightweight, durable form factor that is safe around humans.

Dexterous manipulation requires triangulating reality across multiple modalities:

- **Vision:** What is the object? Where is it?
- **Depth:** What is its geometry and distance?
- **Tactile sensing:** Is it slipping? Is the force correct?
- **Proprioception:** What is the state of the humanoid's joints and body relative to the task?
- **Force and torque sensing:** Is the interaction force within safe and useful bounds?
- **Audio and vibration:** Are there cues that indicate contact, mechanical anomaly, or successful task completion?

While vision and depth dominate discussions of robot perception, audio is often underestimated, but it adds another practical dimension. Sound can detect mechanical anomalies through vibration or acoustic signatures as well as verify actions through distinctive cues, such as the unmistakable **click** that confirms a connector is fully seated and latched.

Tactile sensing supplies what vision and audio cannot: How the interaction is evolving at the contact surface. It enables detection of pressure distribution, vibration, friction transitions, and micro-slip signatures that determine whether a grasp is stable.

This is the hand's hidden truth: Dexterity is as much a sensing + compute + control + AI challenge as it is a mechanical one *(Fig. 5)*.

As humanoid robots move out of cages and into human environments, the intelligence in their hands will matter as much as the strength of their motors. Mastering the hand is what turns humanoids into truly general-purpose machines for real industrial variability. The humanoid hand is where sensing, compute, and intelligence converge — one grasp at a time.

Conclusion: Engineering Trust at the System Level

The hardest problems in humanoid robotics are rarely isolated component challenges. They live at the intersections where sensing meets compute, control meets power, connectivity meets safety. Physical intelligence isn't simply a software layer added on top of robotics hardware. Two humanoids may share similar sensors, motors, and AI models, yet behave very differently in the field. The difference lies in system integration — how timing, signal integrity, power management, and safety are pre-served under real-world variability.

With decades of experience in precision sensing, deterministic connectivity, real-time signal processing, power management, isolation, and functional safety, Analog Devices brings system-level understanding to the most demanding parts of humanoid design. It's not as an abstract technology provider, but as a partner focused on making complex physical systems behave predictably in the real world.

Humanoid robots will not scale because they can walk gracefully or manipulate objects in controlled settings. They will scale when they can operate continuously, adapt to uncertainty, recover from faults, and behave safely alongside people. This is the domain of physical intelligence — AI reasoning aligned with physical constraints.

That future is unlocked by coherent systems engineering, where intelligence, perception, motion, connectivity, power, and safety are co-designed as one synchronized whole. Trusted physical intelligence isn't accidental. It's engineered — one deterministic loop at a time.

As robotics systems evolve, the challenge shifts from adding capability to orchestrating it. A subsequent article will explore this next layer, including a deep dive into co-designing AI with the physical stack, learned policies, skill sequencing, and the data flywheel.

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Reference

Kahneman, Daniel, *Thinking Fast and Slow*. Penguin Random House, October 2011.