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Digital Twins
Changing the way organizations operate

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The term "digital twin" seems to arise from NASA research.

"If various best-physics (i.e., the most accurate, physically realistic and robust) models can be integrated with one another and with on-board sensor suites, they will form a basis for certification of vehicles by simulation and for real-time, continuous, health management of those vehicles during their missions. They will form the foundation of a ***Digital Twin****."*

— **Stargel and Glaessgen**, The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles, 2012

In 2017, Gartner ranked digital twins as technology trend #5.
In 2018, it rose to become the #4 technology trend.

"Within three to five years,
*billions of things will be represented by **digital twins**,*
*a **dynamic** software model of a physical thing or **system**.*
...
a digital twin can be used to analyze and
simulate real world conditions,
respond to changes,
improve operations and add value."

Gartner®

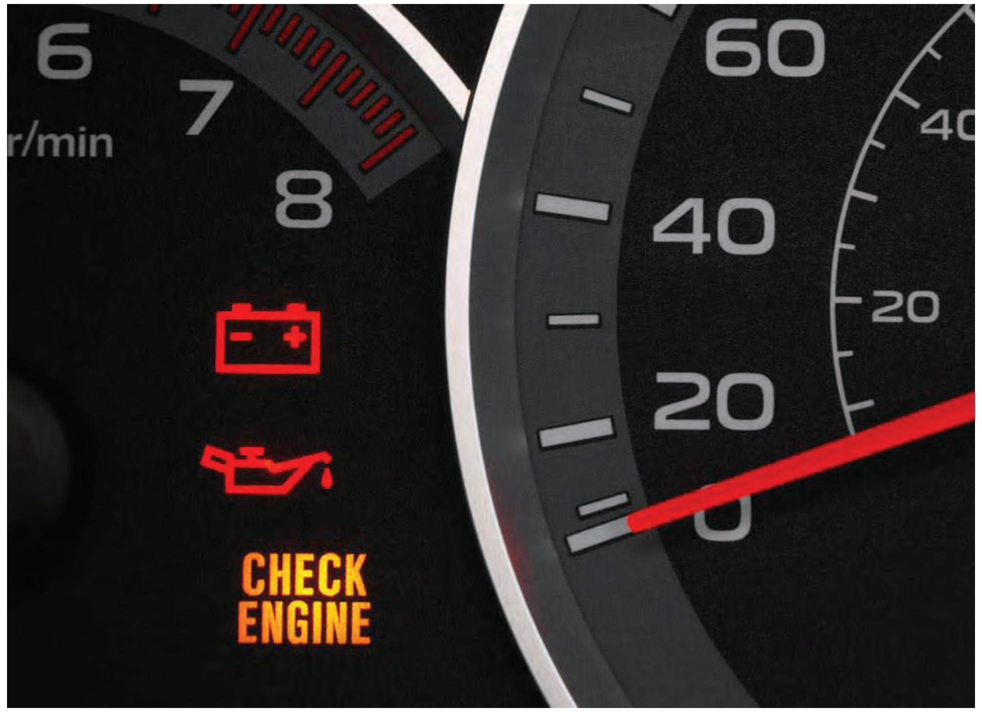
— **Gartner**, Top 10 Strategic Technology Trends, 2017

Dynamic systems need on-going maintenance, to minimize wear, service disruption, and repair costs.

Car makers recommend changing engine oil every 3,000–10,000 miles, to optimize engine performance and extend life.

Things can go wrong between oil changes, i.e., a leak; over time, car makers added tools to monitor failure points.

Dipstick

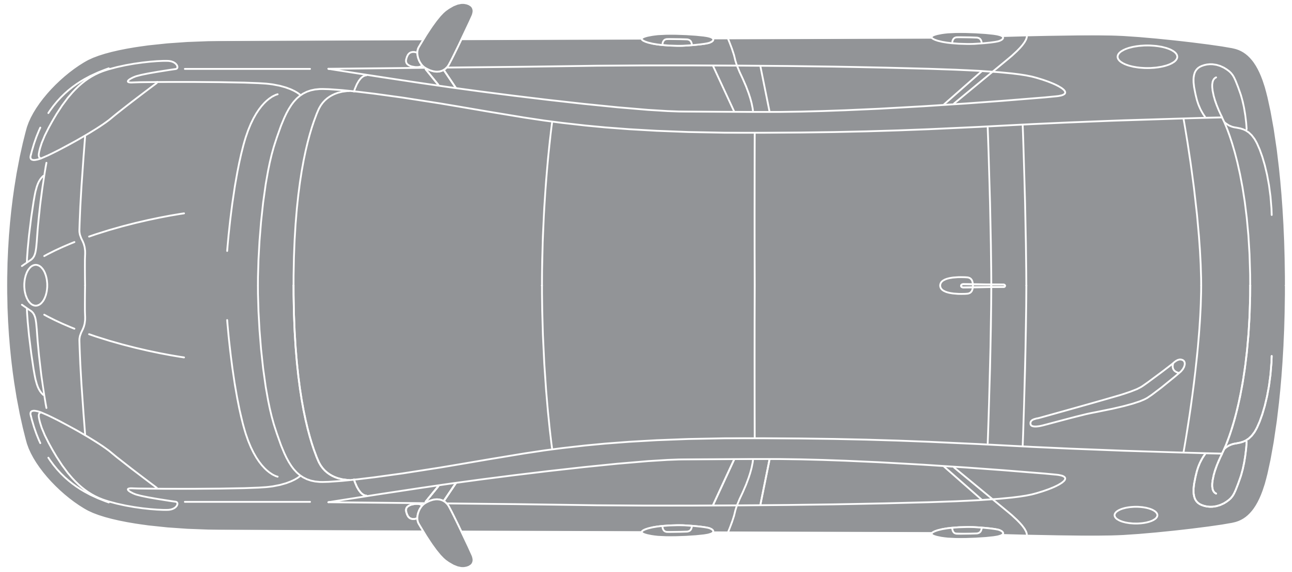


Check Engine Light

On-Board Diagnostics (OBD) Port

Mechanical systems have been supplemented with digital systems, generating as much as 1TB of data[1] per car per day.

~ 60–100 sensors
(growing to 200 by 2020)[2]
~ 30 micro processors
(up to 100 for luxury cars)[3]
~ 100 million lines of code
(up from 2 million lines in a generation)[4]
- connectivity (phone, internet, car-to-car)



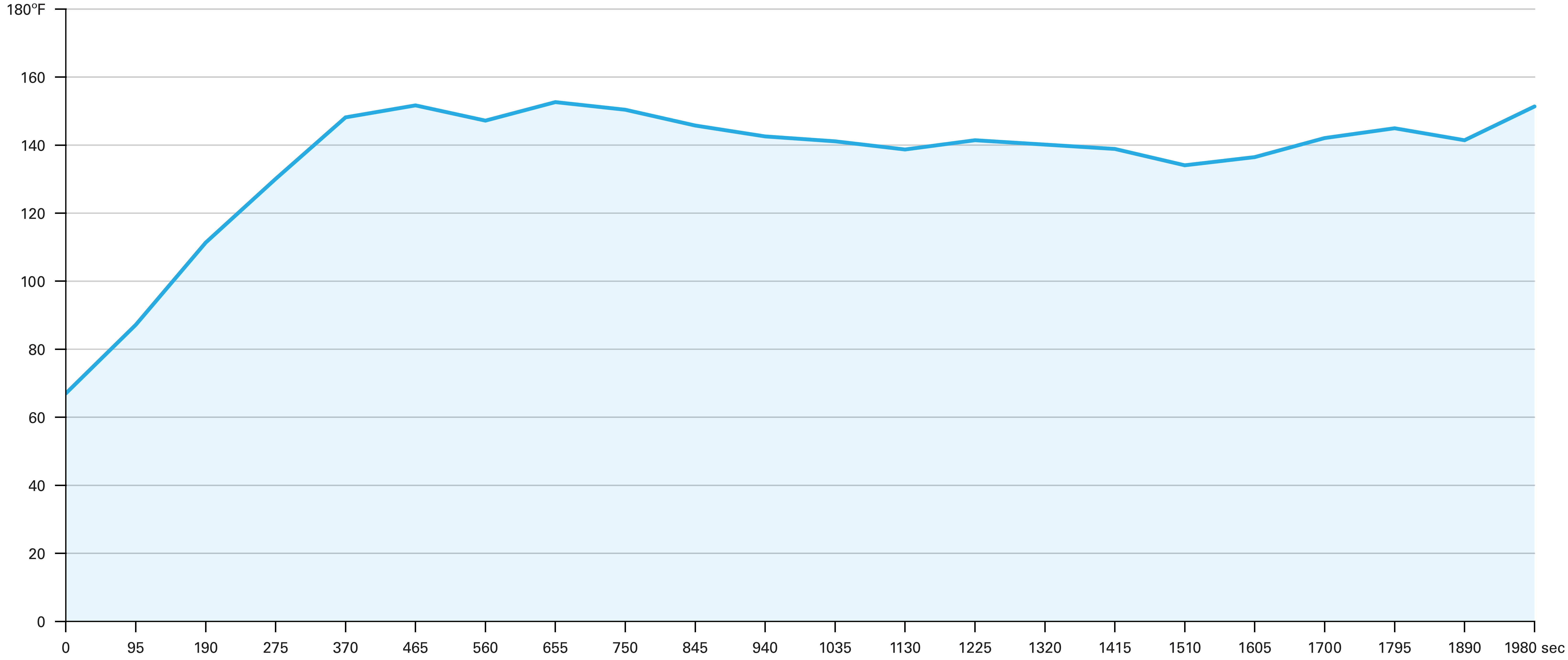
Sources:
[1] Parrish Hanna, Global Director of HMI at Ford (personal communications)
[2] http://www.nytimes.com/2010/02/05/technology/05electronics.html
[3] http://www.automotivesensors2015.com/
[4] https://leithporsche.com/news/What+Makes+the+2017+Porsche+Panamera+Different3F+Computer+Code/7659/

Data describes the current state of the system.

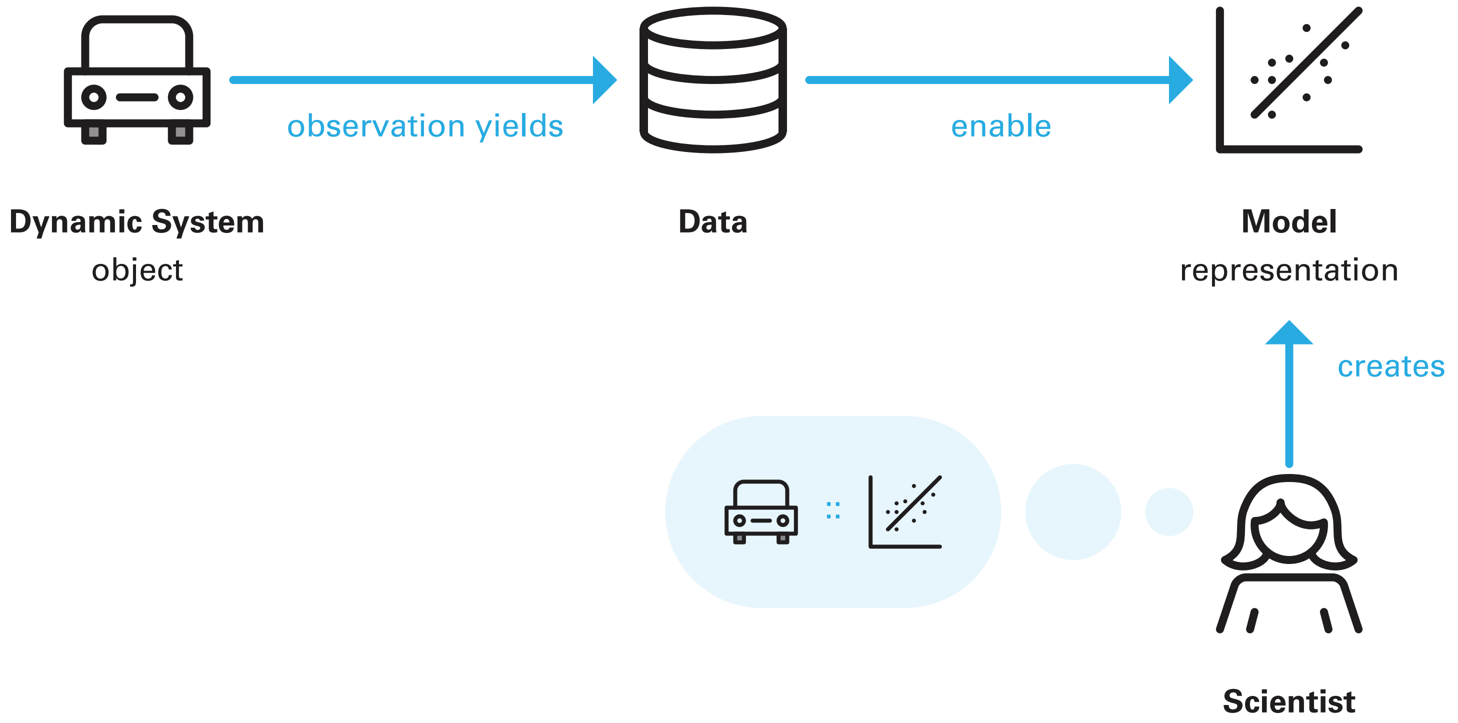
Engine oil temperature gauge

Preserving data creates an historical record.

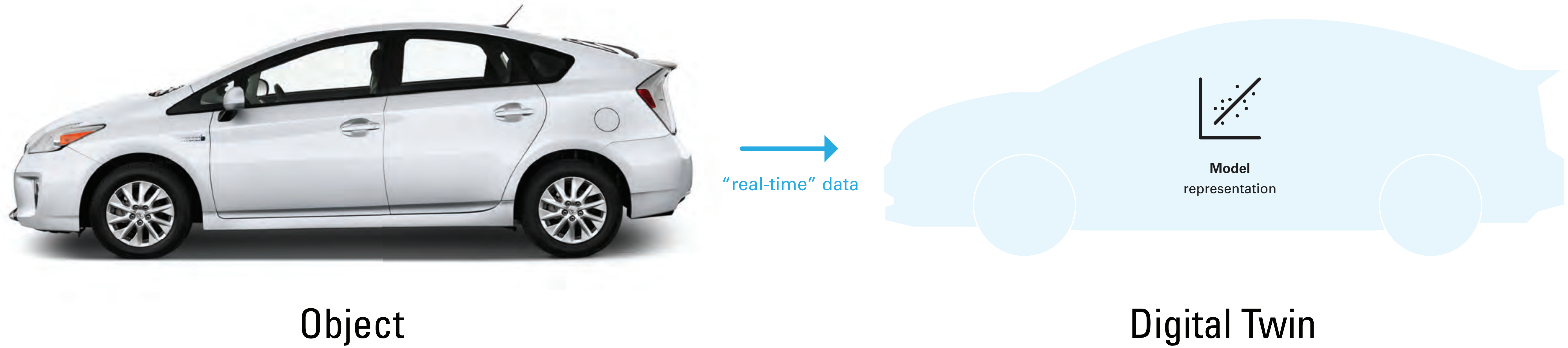
(Engine oil temperature over time)



Enough historical data enables modeling—codifying patterns and relationships found in the data.



This model becomes a "digital twin" for your car.



Data and models can predict when failures are likely, so that maintenance can be performed to prevent them.

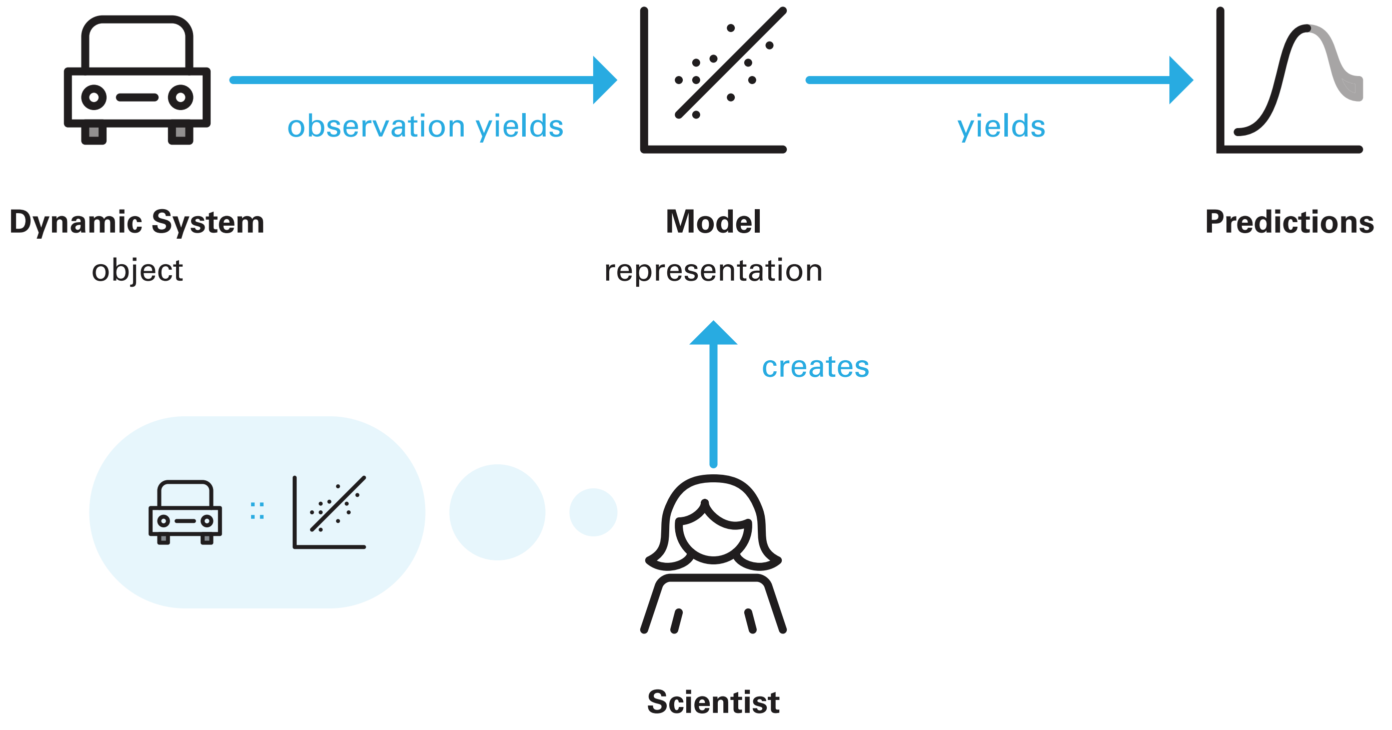
I.e., pinpointing the optimal time to change oil,
or anti-freeze, or breaks, etc.

Engine sludge

Worn out brake

Worn out tire

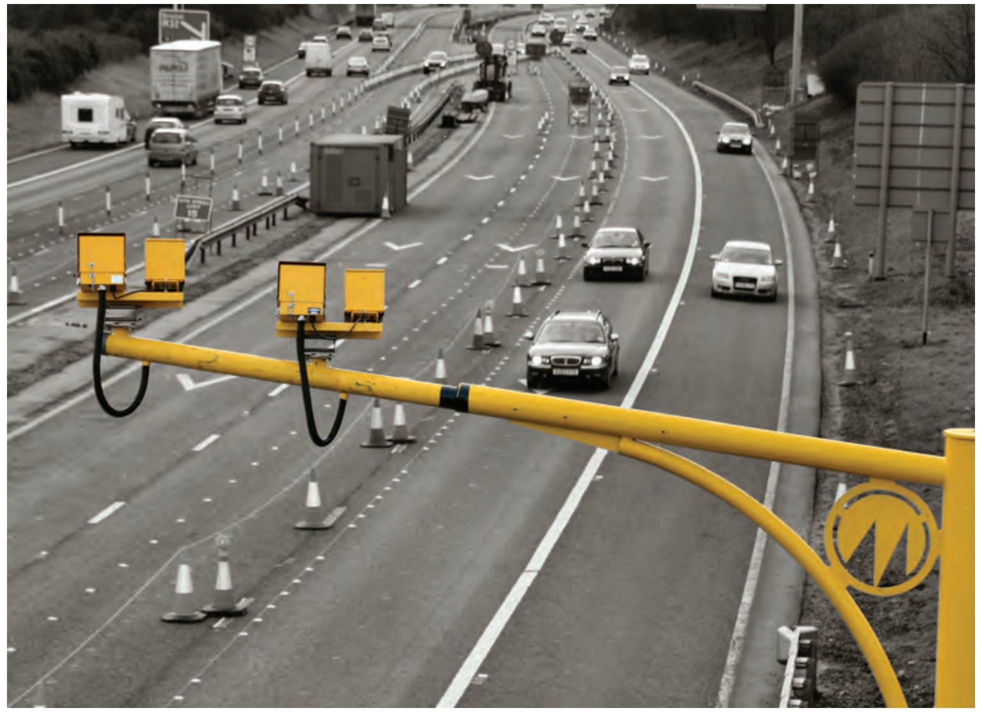
Given new observations, models predict the future.



In addition, data can help us understand context and behavior, improving the model's robustness and reliability.

Global Positioning System (GPS)

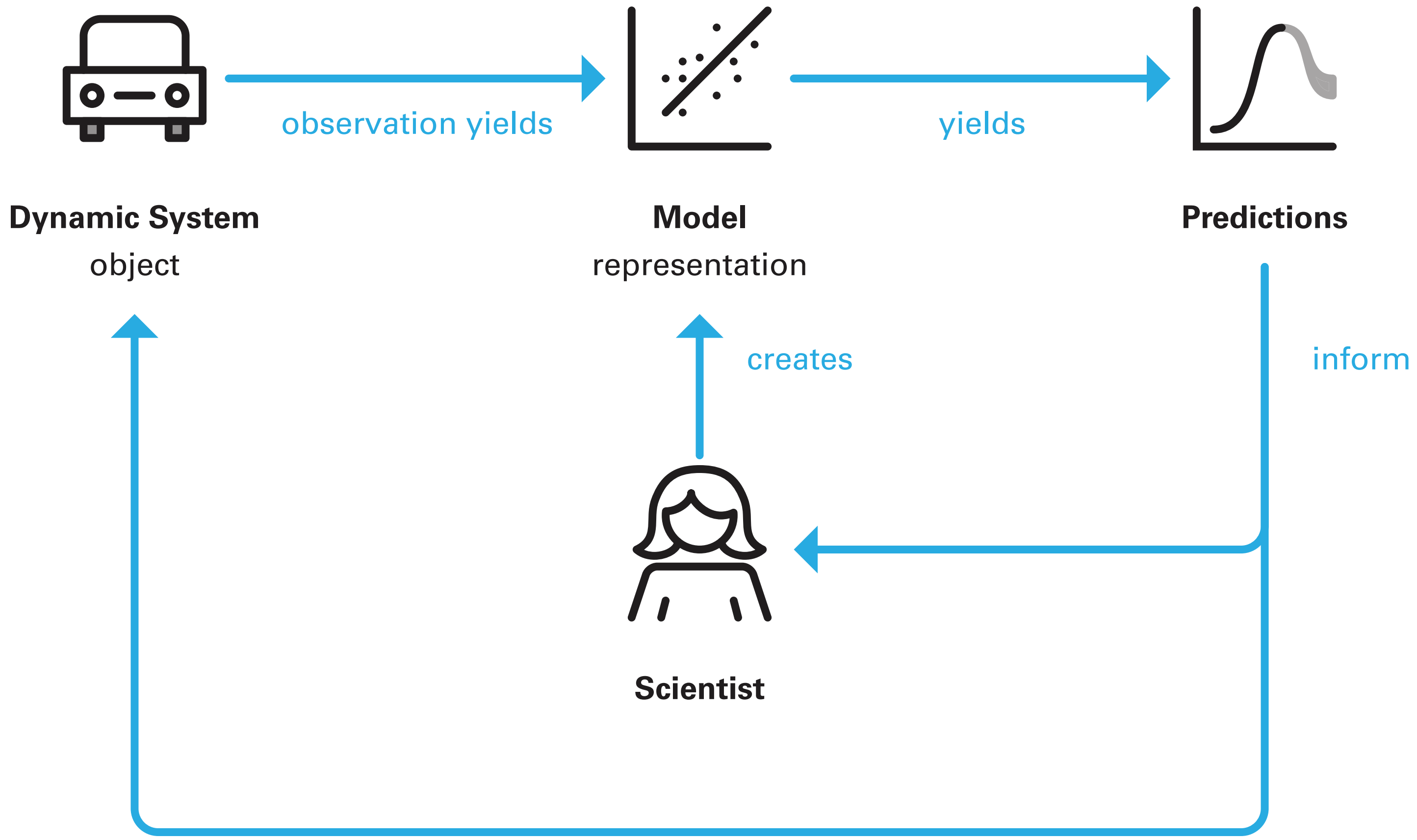
Electronic Toll Collection (ETC)



License plate reader

Adding context and behavior to the digital twin, enables action:

- Do nothing
- Human decides to act
- Automated action



Automated actions begin in tightly defined special situations.

Anti-lock Braking System (ABS)

Emergency Brake Assist (EBA)

Intelligent Parking Assist System (IPAS)

With sufficiently robust digital twins, self-driving cars are possible.

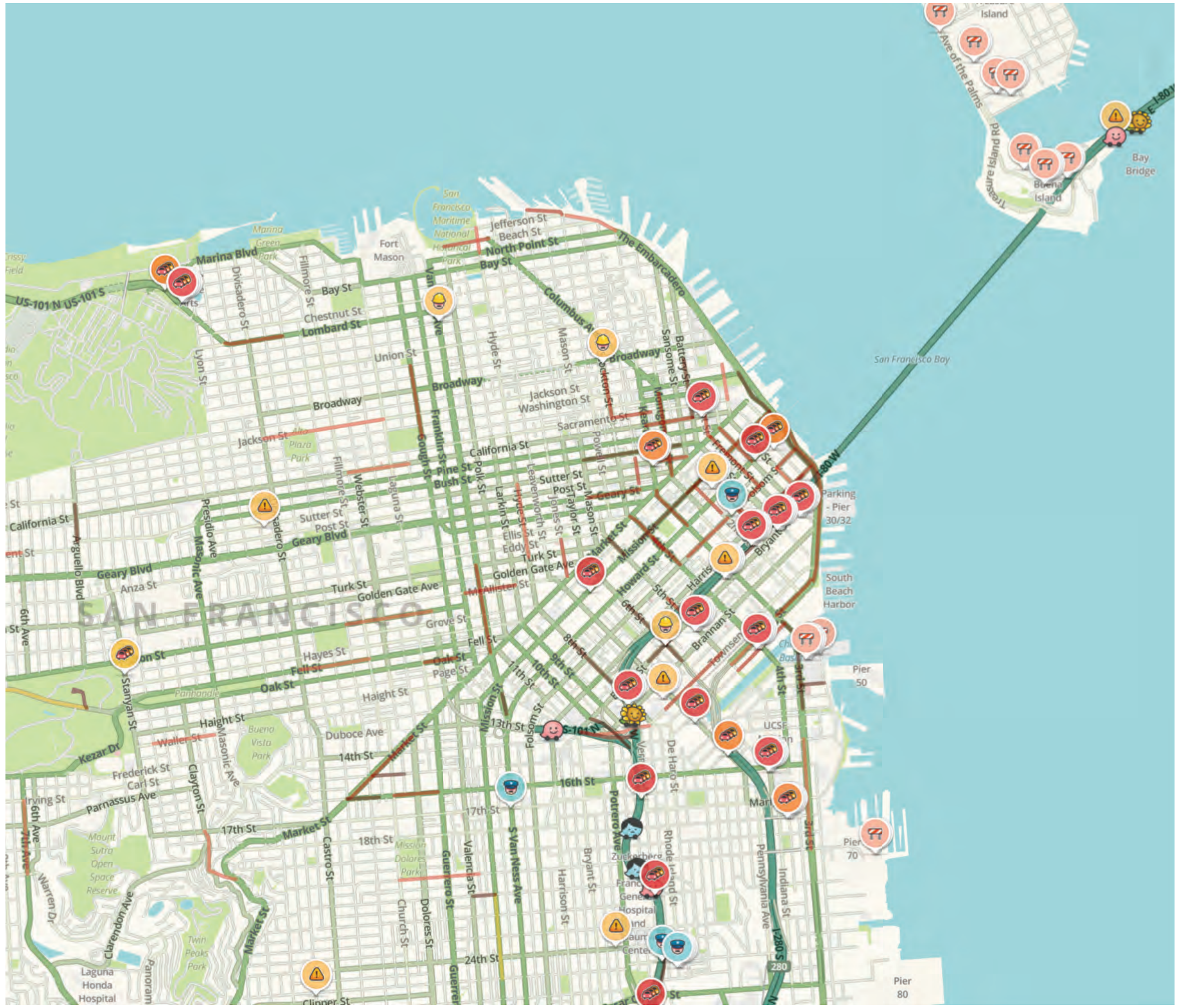
Digital twins will be everywhere, in the small, and in the large.

Cruise control

Digital twin of speed

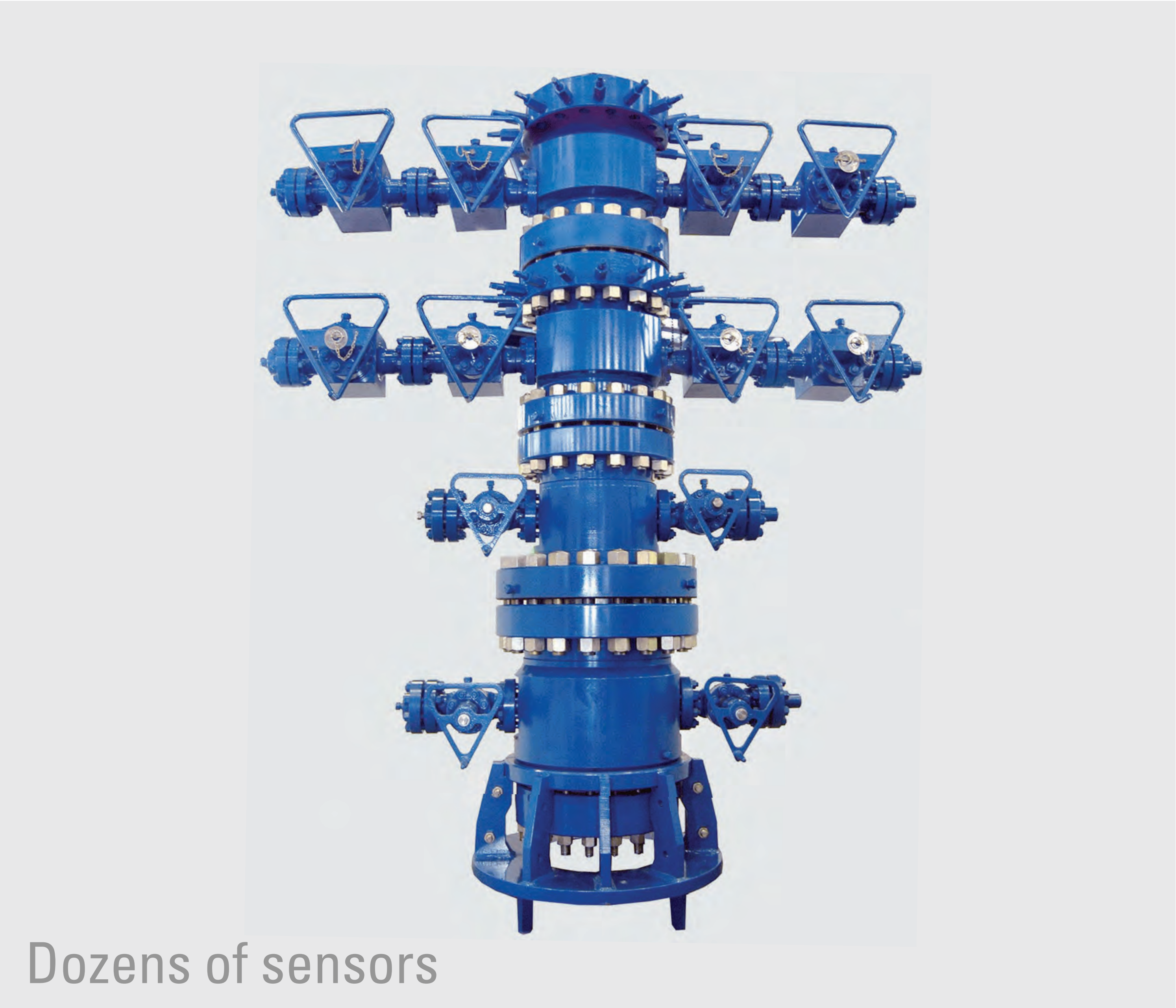
Waze live map

Digital twin of traffic, travel time



Wellhead

Digital twin of individual oil well



Oil platform

Digital twin of aggregate production

Individual package tracking

Digital twin of location, provenance

Package type tracking

Digital twin of performance, breakage

Continuous Glucose Meter (CGM)

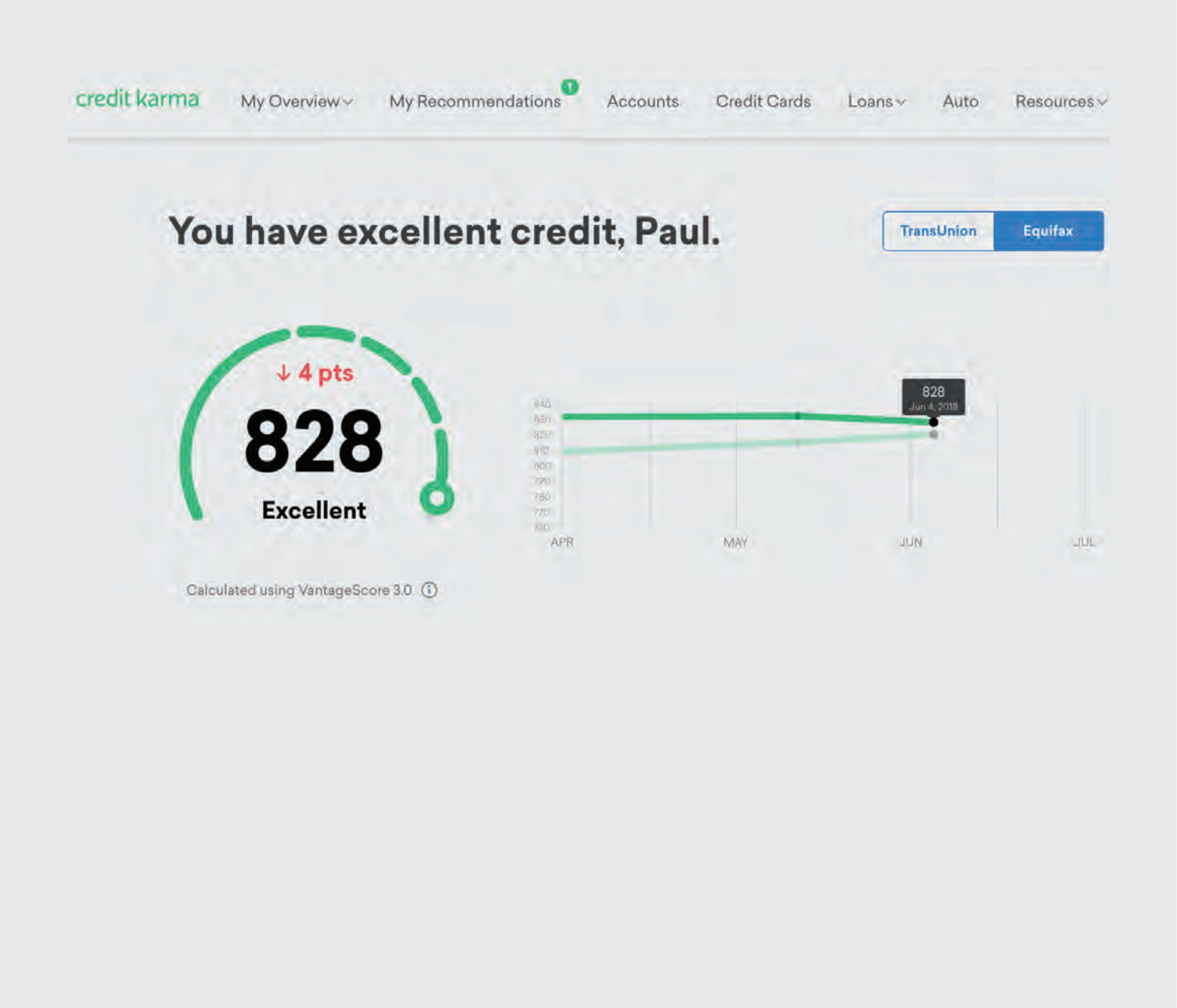
Digital twin of blood glucose

Patient population management

Digital twin of collective health

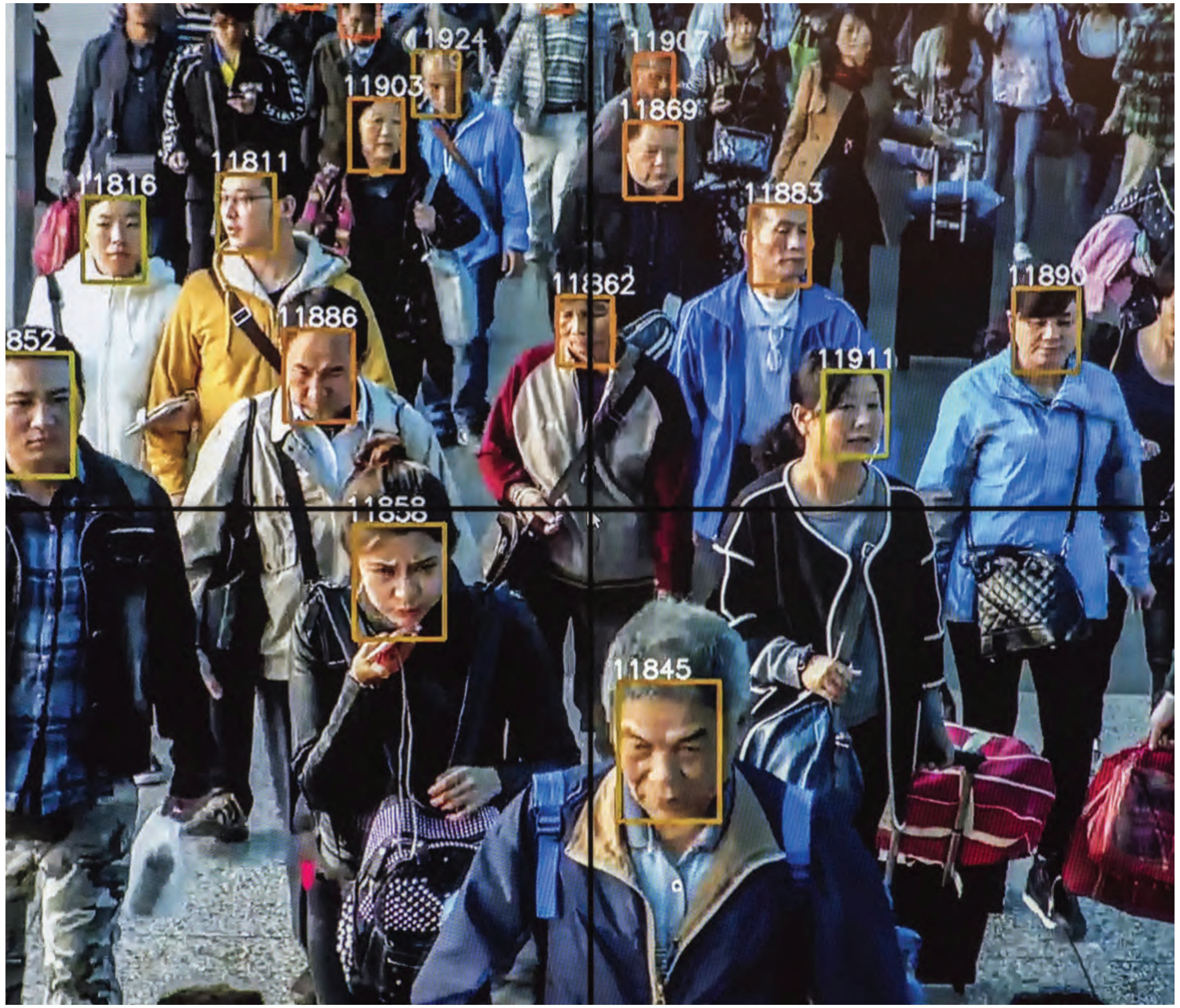
Personal finance

Digital twin of credit, bank account



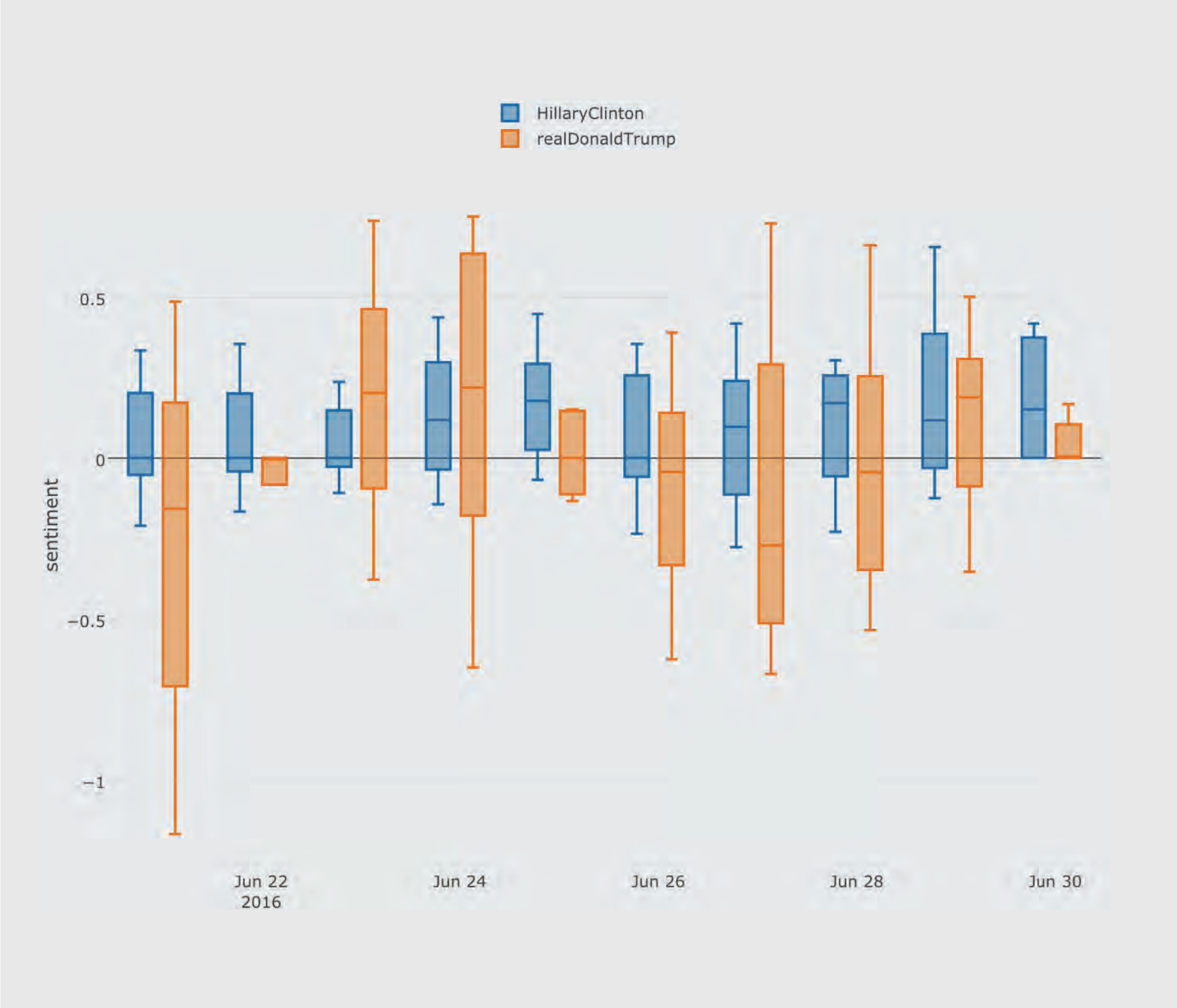
Social credit score

Digital twin of behavior



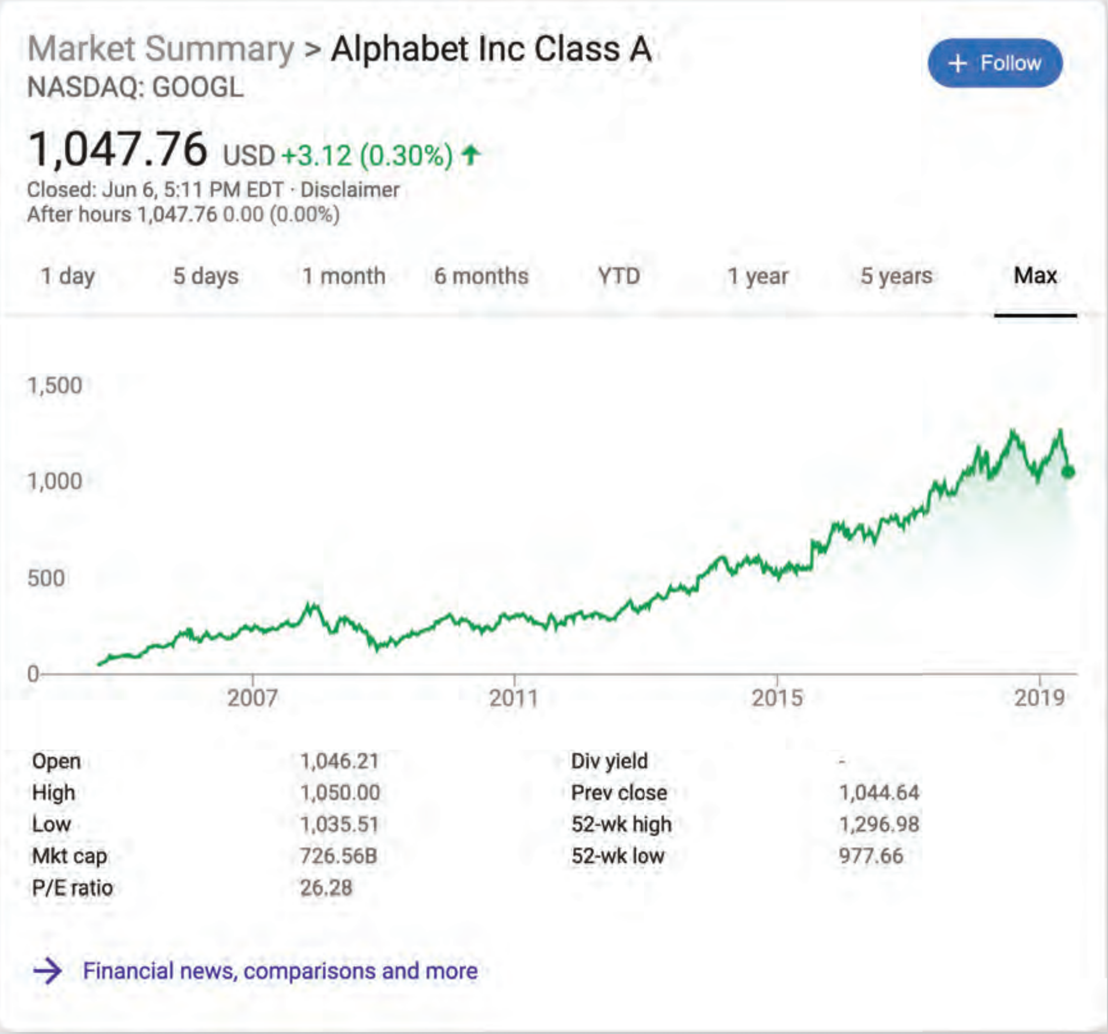
Twitter news feed + ad service
Digital twin of individual interests

Twitter aggregation
Digital twin of group sentiment



Stock price

Digital twin of company's health



Stock index

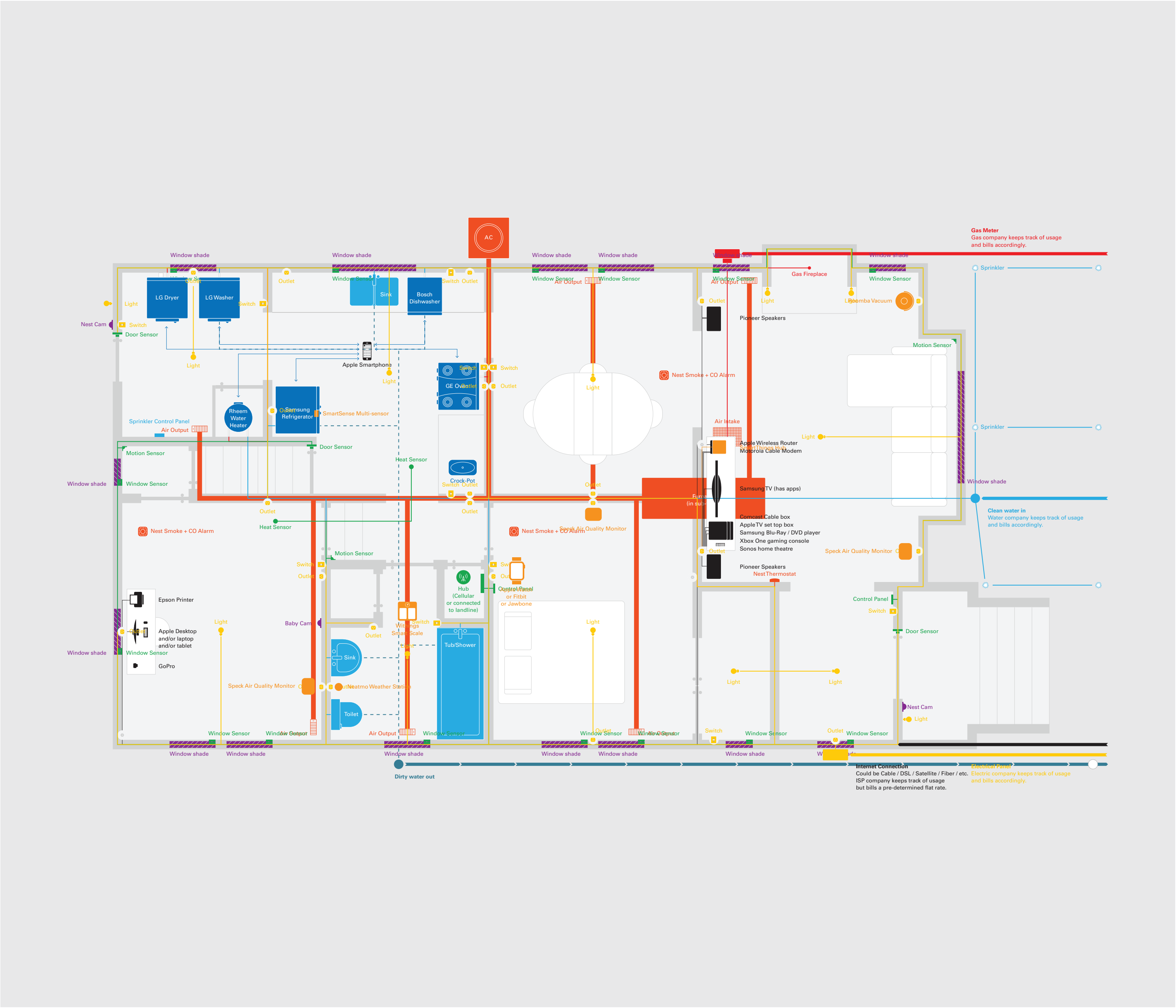
Digital twin of economy's health

Home temperature

Digital twin of comfort

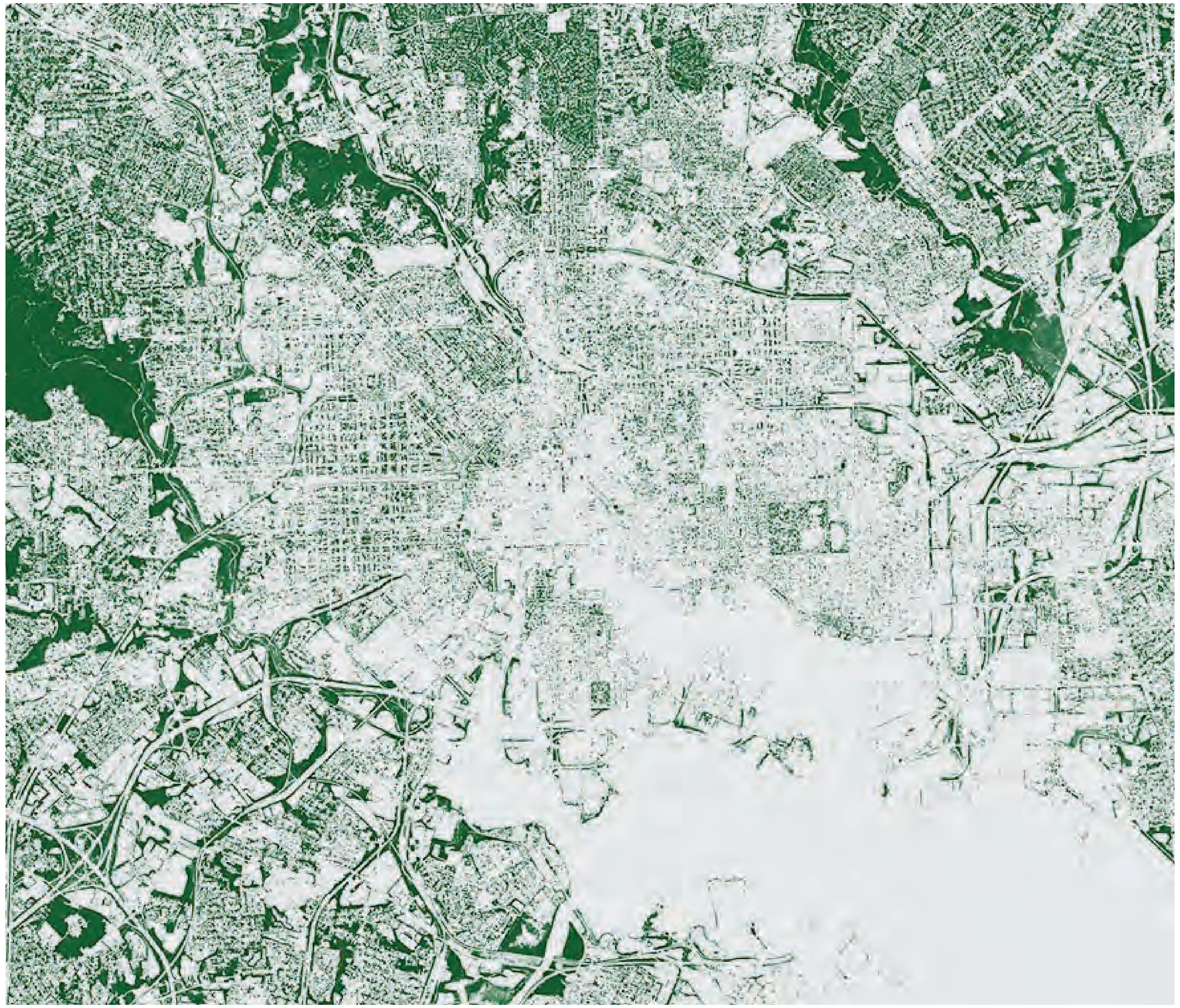
HVAC is one of many home systems

Each will have a digital twin



Urban forest monitoring

Digital twin of forest health



Rainforest monitoring

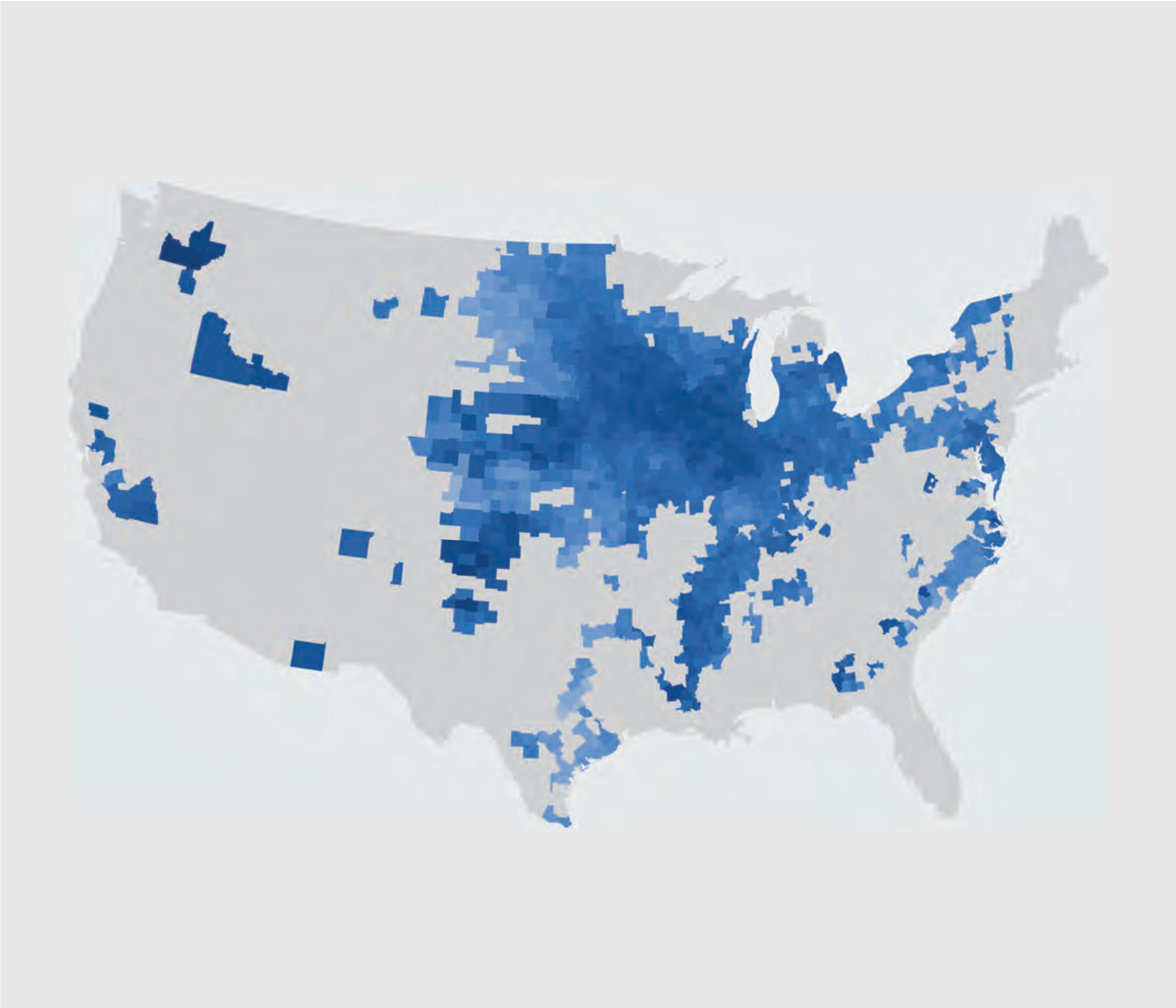
Digital twin of deforestation

Wine production monitoring

Digital twin of grape ripeness

Corn production monitoring

Digital twin of corn yield in the US



Individual location inventory

Digital twin of stock

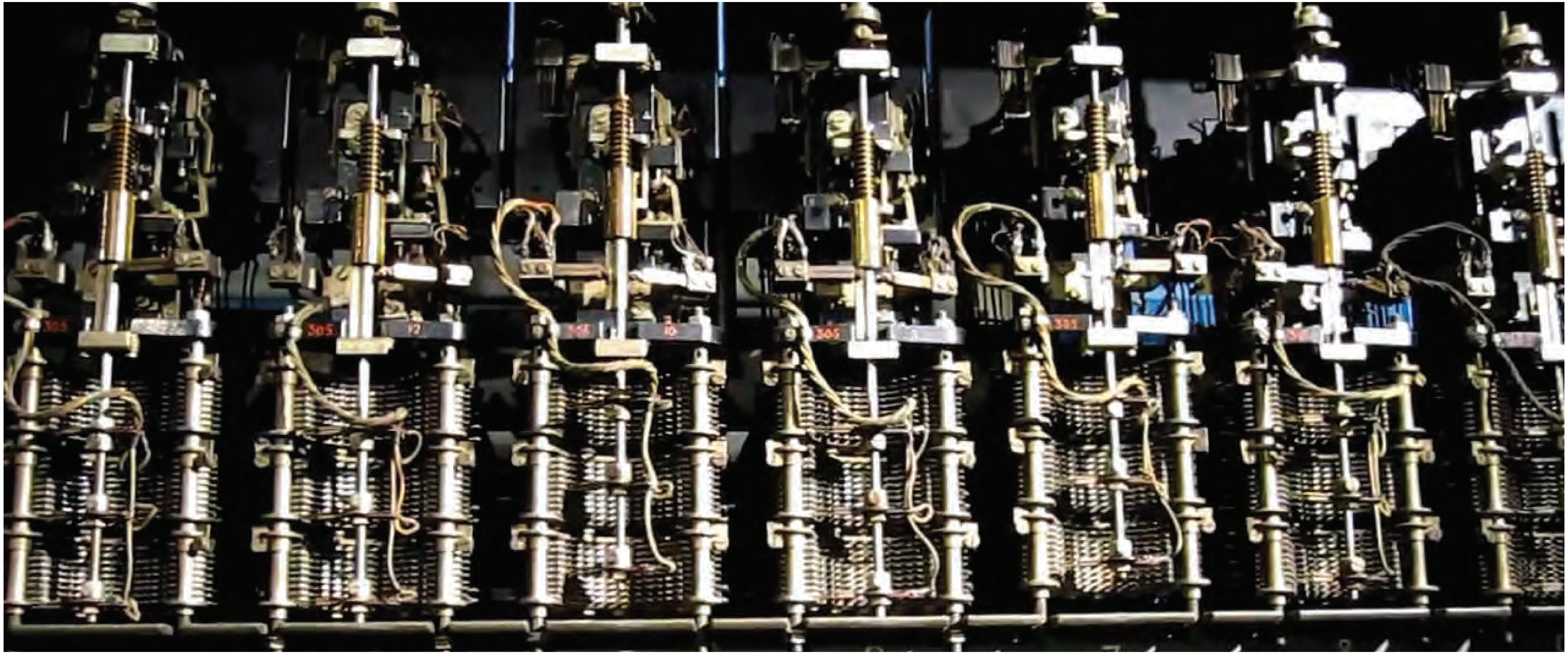
Supply chain

Digital twin of stocks and flows

What would a digital twin of the whole Earth be?

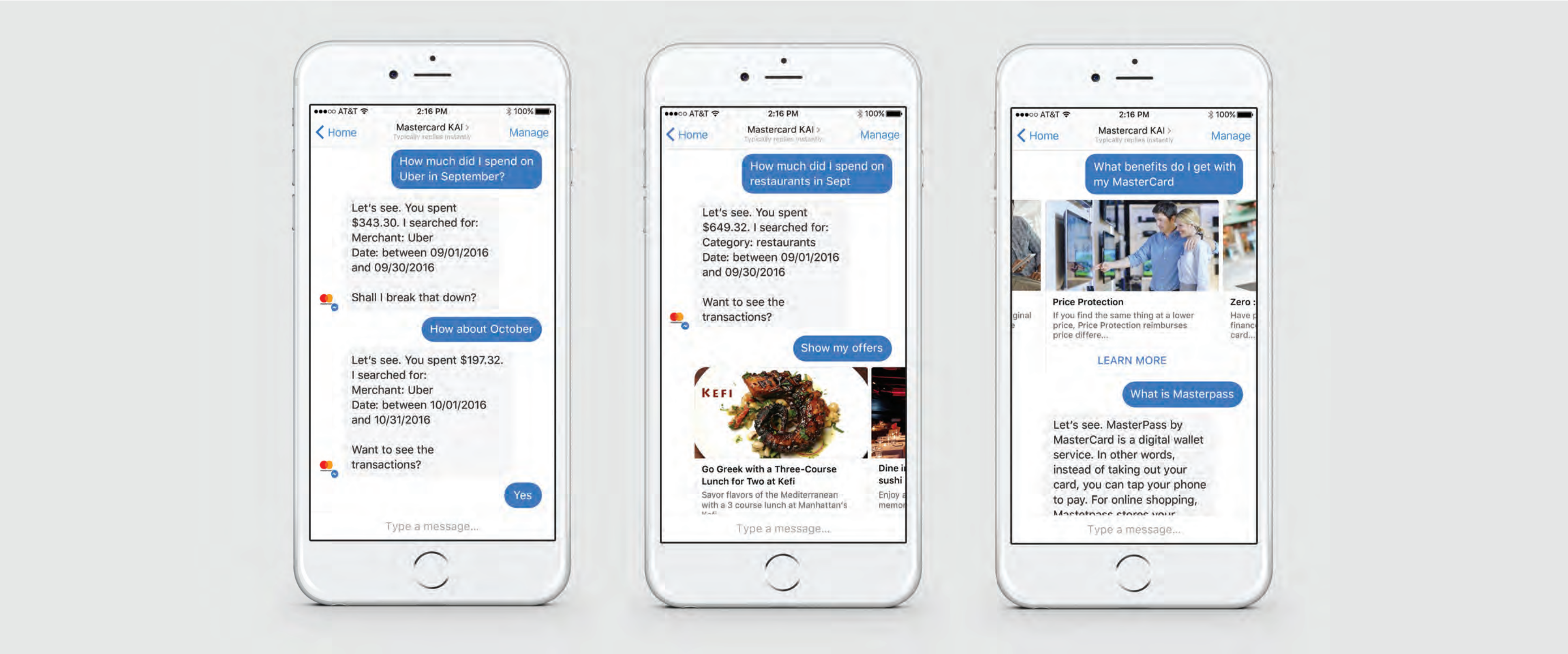
Digital twins coupled with ‘intelligent agents’ will change the way organizations operate.

Quality and costs will be even more closely controlled.



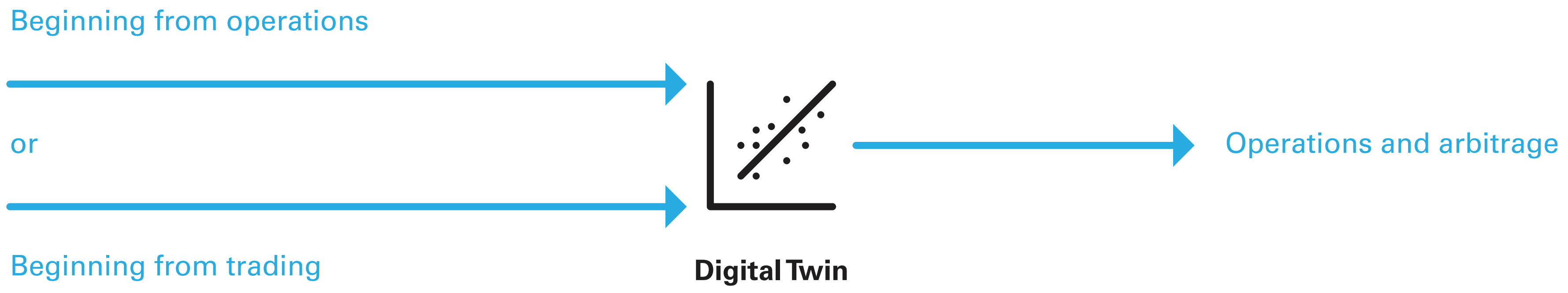
Production processes and output will be even more tightly managed.

Services will become automated—digital twin + intelligent agent = self-driving organization



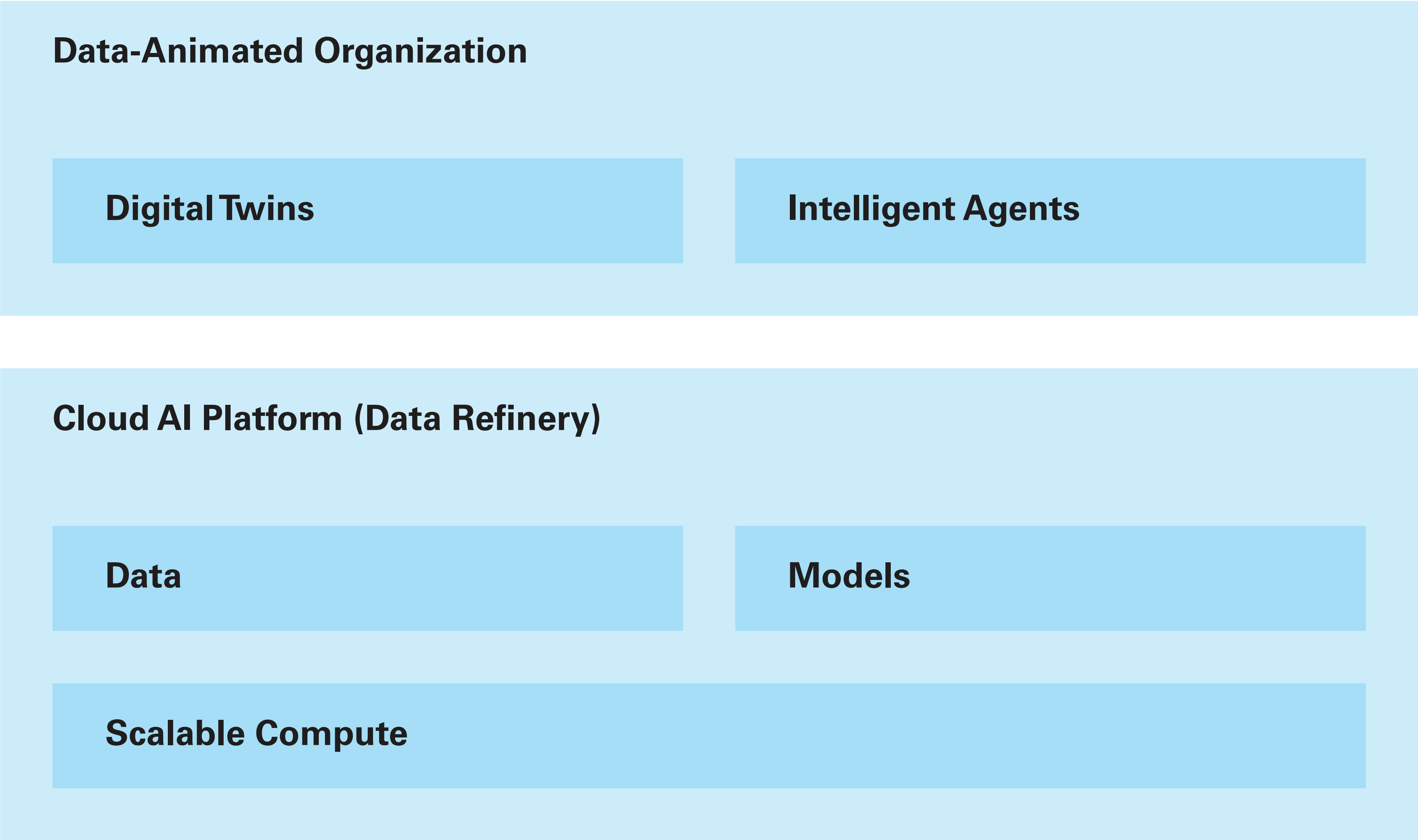
Some organizations will enter the world of digital twins in order to further "quantify" their trading strategies.

Ultimately, digital twins will become requisite for both operations and arbitrage.



The world's most influential organizations already build digital twins.

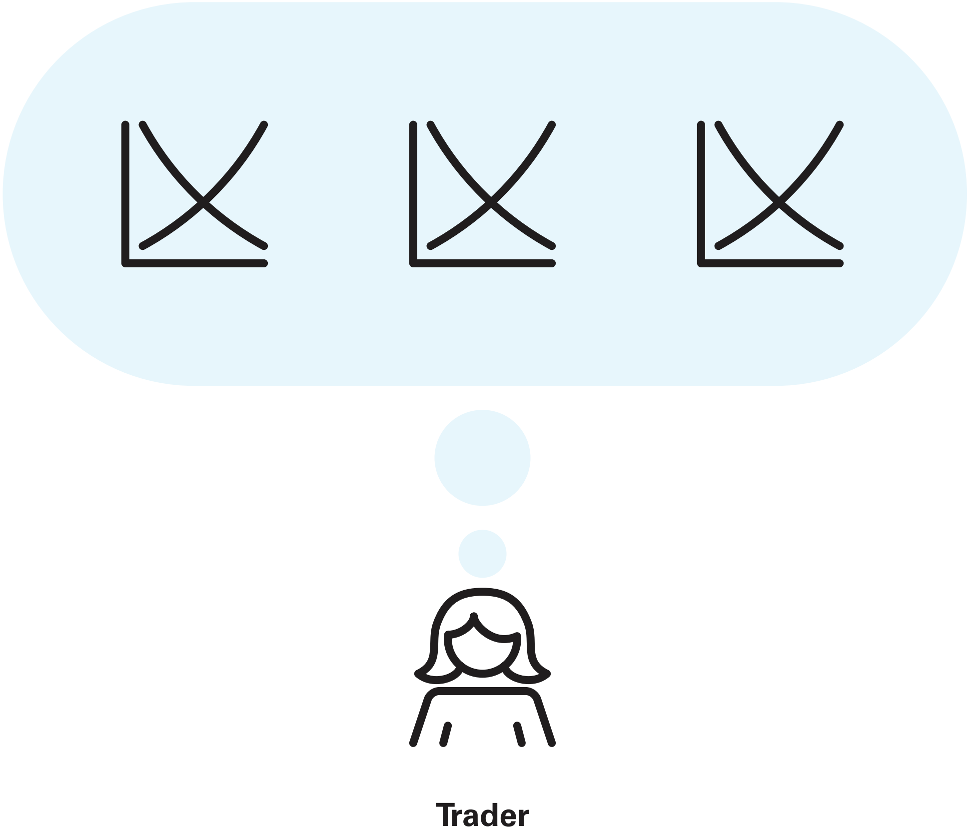
Digital twins require a platform; early adopters are DIY, but ultimately digital twins will run on cloud AI platforms.



Digital twins in trading

Trading (buying and selling) requires a model of supply and demand (originally, the “fundamentals”).

“Understand the ‘fundamentals’, and you will understand price.”



Rational traders base their models on evidence; that has often meant visiting farms and calling contacts.

Since everyone has a different view, their models are different; essentially traders are betting on the validity of their models.

If their models proceed a series of successful trades, traders can become “wedded” to them — believing they produce “alpha”.
(An effect of “sunk costs” may be at work here, too.)

Trading on fundamentals relies on domain knowledge and social networks, thus limiting what an individual trader can know.

Digital communications networks offer much more data, and with sufficient computing, ML can find patterns — enter “quants”.

Quant models are subject to more rigorous testing
and are updated as new data and new results become available.
They evolve continuously.

Quant models of commodity production (supply) are a type of digital twin.

Digital twins of commodity production can be quite granular — county, farm, field, even individual plants.

Quants generate many alternative models (lower cost per model).

In a quant world, it makes sense to test fundamental models and ensure that they are valid — still producing “alpha”.

Older fundamental models may no longer confer advantage and new factors may also be at play.

Now that testing is fast and cheap,
testing old models and new factors makes good business sense.

Traders may also build digital twins of demand and compound twins of larger supply chains.

Before quants, what individual traders could see and understand limited what they could trade on.

Now, with digital networks, cloud computing, and AI platforms, traders can increase the scope of their activities — and their confidence!

Application of digital twins

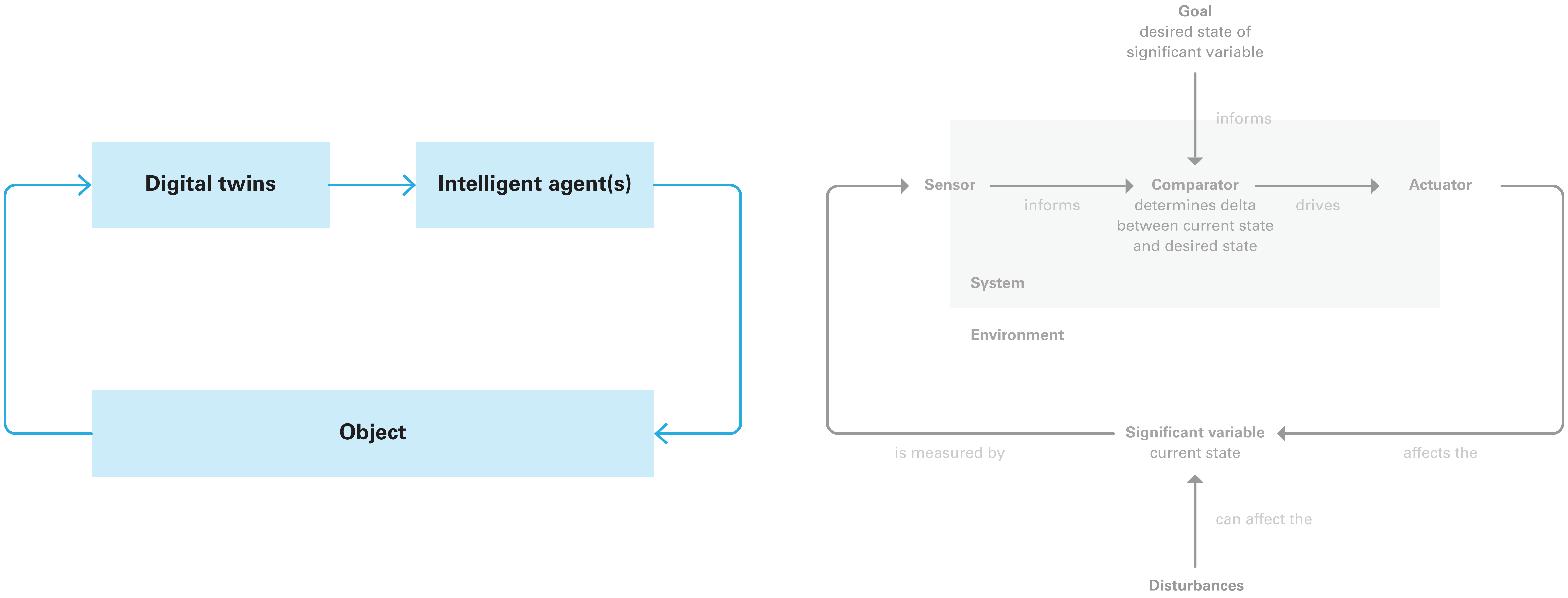
Digital twins can be applied in three ways:

1. Reporting the current state of their objects.

2. Making predictions based on new data.

3. Controlling systems — “operations”

The operational side of a digital twin is an “intelligent agent”.



An "intelligent agent" is a software algorithm that evaluates predictions made by digital twins and matches them with possible actions.

For example, a digital twin of corn production will calculate effects of precipitation on production; intelligent agents may use those predictions to drive a range of activities—from irrigation to trading.

Like digital twins, intelligent agents require a platform.

The relation of twin to agent need not be one-to-one; it may also be one-to-many, many-to-one, or many-to-many.

Given that ideal configurations are often unknown in advance, a service architecture makes sense.

Taxonomy of digital twins

Simple twins

The simplest twins represent a single variable
and model its relation to a threshold (or thresholds),
e.g., temperature, steam pressure, speed, blood glucose level, etc.

Multi twins

Adding other (significant) variables tends to increase the fidelity, reliability, and utility of the twin, e.g., multiple temperature sampling points, such as upstairs, downstairs, basement.

Compound twins

A digital twin may bring together multiple variables,
i.e., “compound twins”,
e.g., temperature and humidity
(which when plotted in an x-y matrix form an
area we might reasonably call a “comfort” zone.

Nested twins

Building a twin of an object with sub-systems
may require twins of the sub-systems,
i.e., “nested twins,”
e.g., a twin of an AC system may need twins of
temperature, humidity, compressor speed, coolant pressure,
fan speed, filter cleanliness, rate of air flow, etc.

All or some of these may be multiplied by
the number of “zones” in the building.

Air quality (particles, VOCs, etc.) compound complexity of the twin.

Thick twins

Twins that are “robust” or “high-functioning” tend to be both nested and compound, as in the AC example.

Consider also,
e.g., a twin of corn growth in the US requires
twins of growth in sub-regions,
i.e., counties, each of which has different soil, elevation, latitude, temperature, precipitation, etc.

In fact, each pixel in the satellite image may be a twin,
i.e., an NDVI value changing over time,
which is a proxy for plant growth.

Outside twins

Likewise, adding a model of the object’s environment may add utility,
and may enable the twin to interact with its environment,
e.g., a digital twin of a jet engine need not include
a twin of the engine’s environment;
however, a digital twin of a self-driving car without some model of
its environment would be “blind” and unable to function.

(Digression:
Lear asks, “No eyes in your head... ? ... yet you see how this world goes.”
And Gloucester replies, “I see it feelingly.”...
Somewhat later, Cordelia says, “Be govern’d by your knowledge,
and proceed I’ the sway of your own will.”)

Twin populations

Management of populations suggests twins of all individuals in the population.

For example:

- Patients enrolled in a Kaiser health plan
- Aircraft approaching JFK
- Grain silos owned by Cargill

Learning twins

Simple twins are often developed by inspection, i.e., by ascertaining what can be measured relatively easily and what the participants agree is a “reasonable” threshold of concern or comfortable range. However, if a twin has resulted in collecting a history, patterns may be found using the methods of statistics and machine learning. Thus, more elaborate models can be built and incorporated in the twin. A further process may be added, which updates the model as more historical data becomes available. If the twin is part of a system which acts in an environment (e.g., making predictions), then predictions may be compared to actual results, and the model’s accuracy may be improved — a type of learning may take place.

Twins needn't be digital

Listing of rations paid out

Clay tablet from the Third Dynasty of Ur (circa 2027 BCE)

Antikythera mechanism

Predicting astronomical positions and eclipses (circa 87 BCE)

Centrifugal governor (flyball governor)

By Christiaan Huygens (17th century), popularized by James Watt (1788)

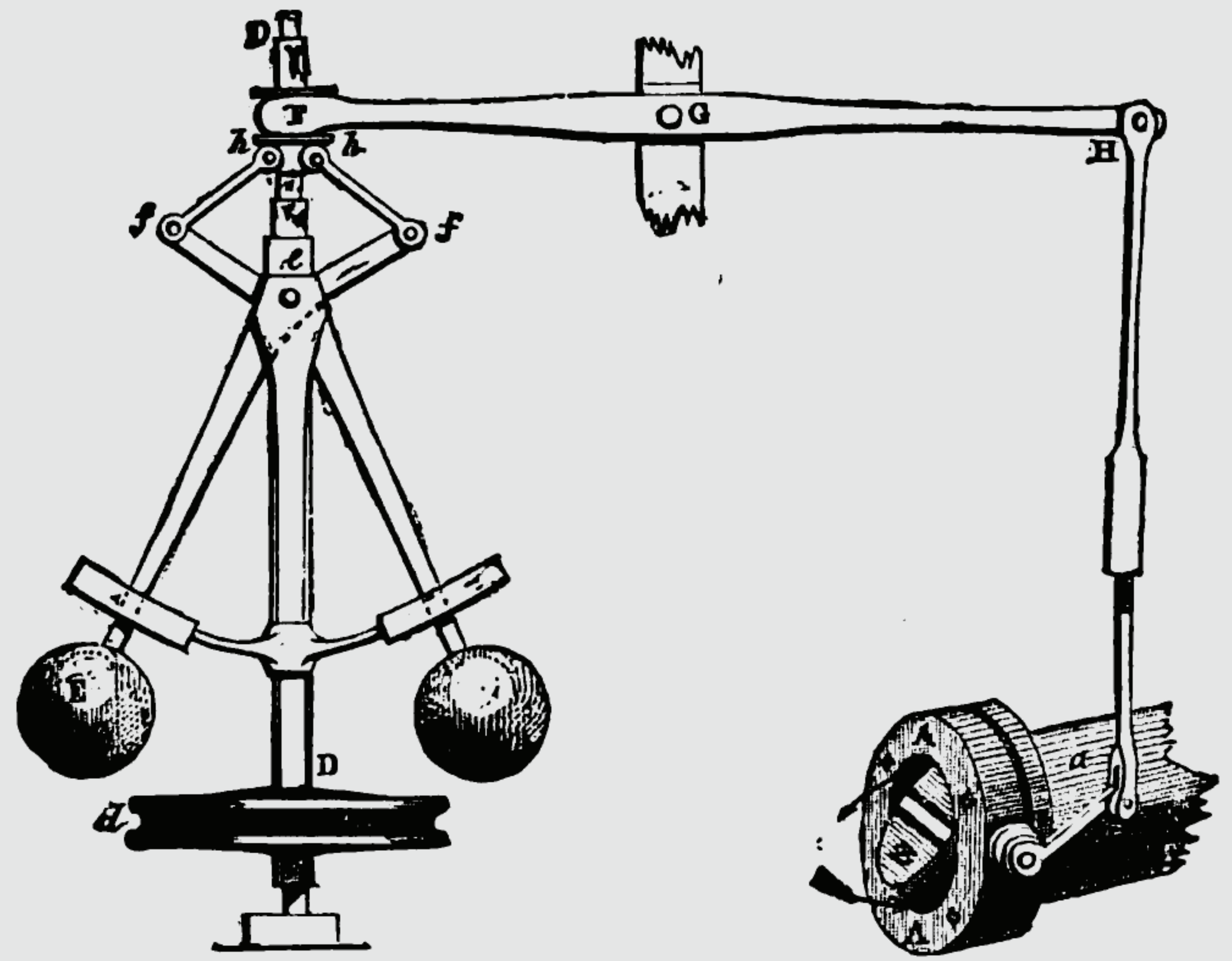


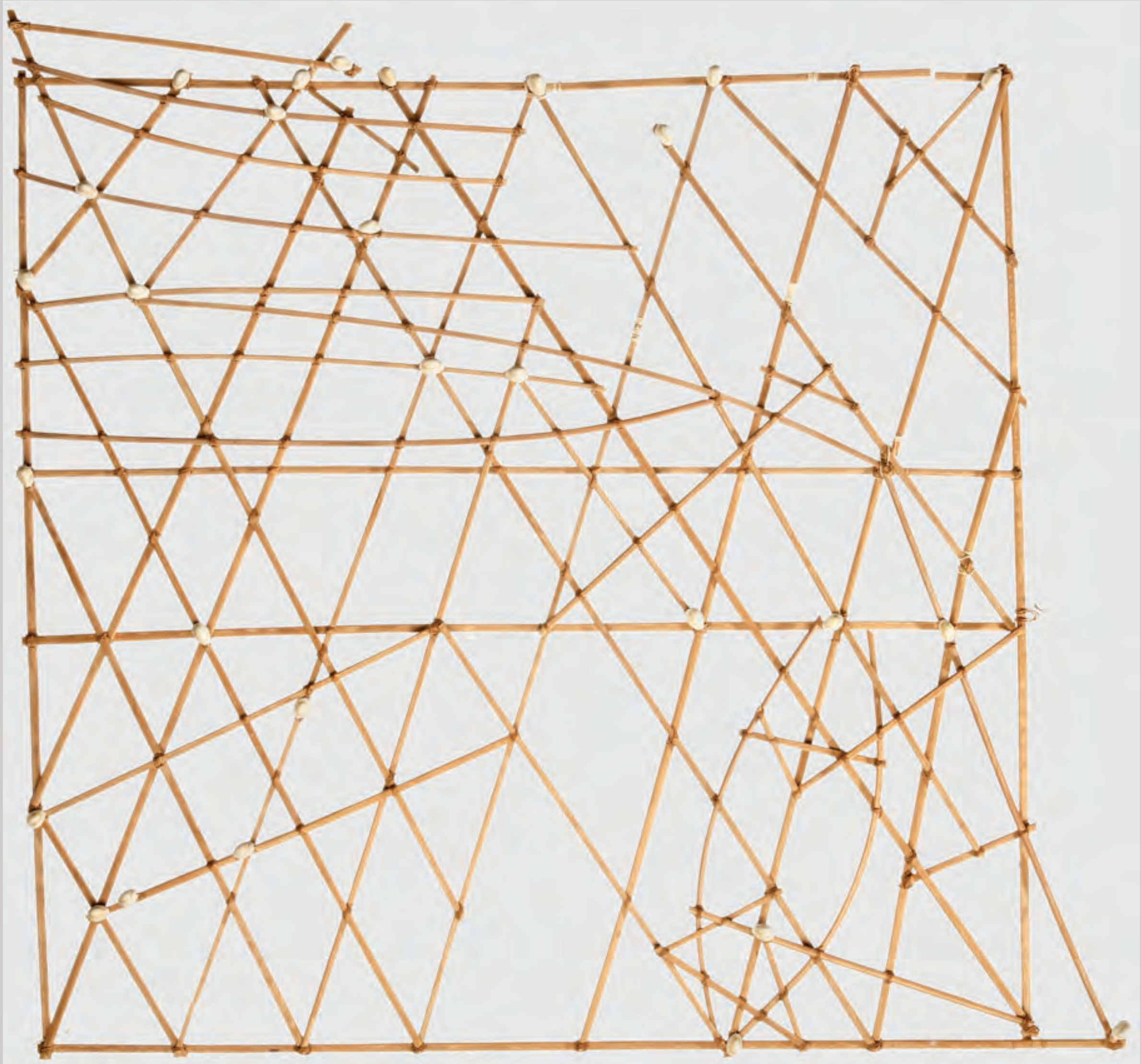
FIG. 4.—*Governor and Throttle-Valve.*

Accounting worksheets— precursor to electronic spreadsheets

German ledger from 1828

Marshall Islands stick chart

Representing ocean swell patterns and how island’s affect it, 1862



Mississippi river basin model

Built between 1943–1966

Monetary national income analogue computer (MONIAC)

Built in 1949

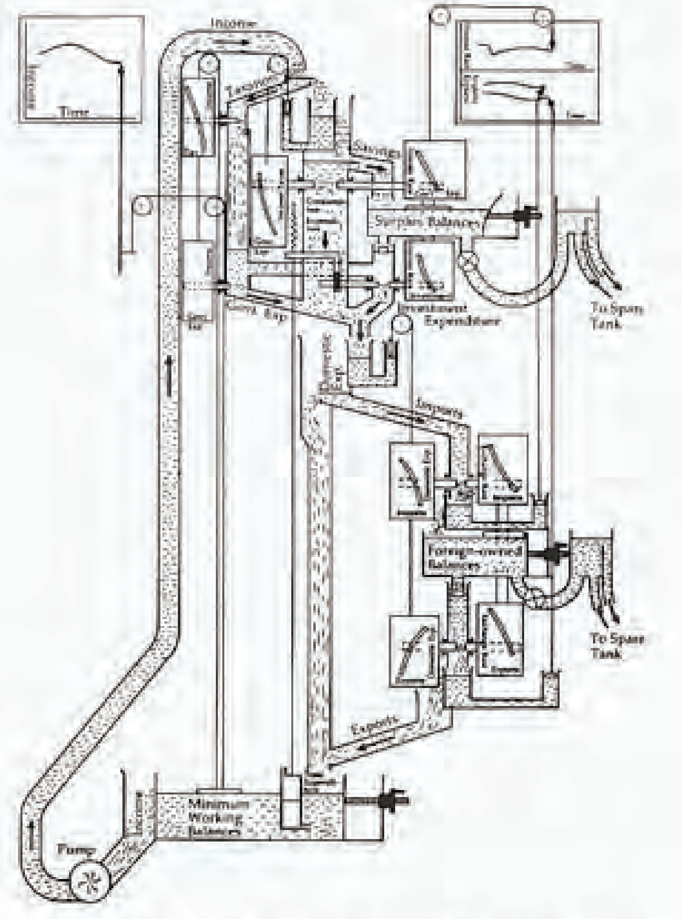
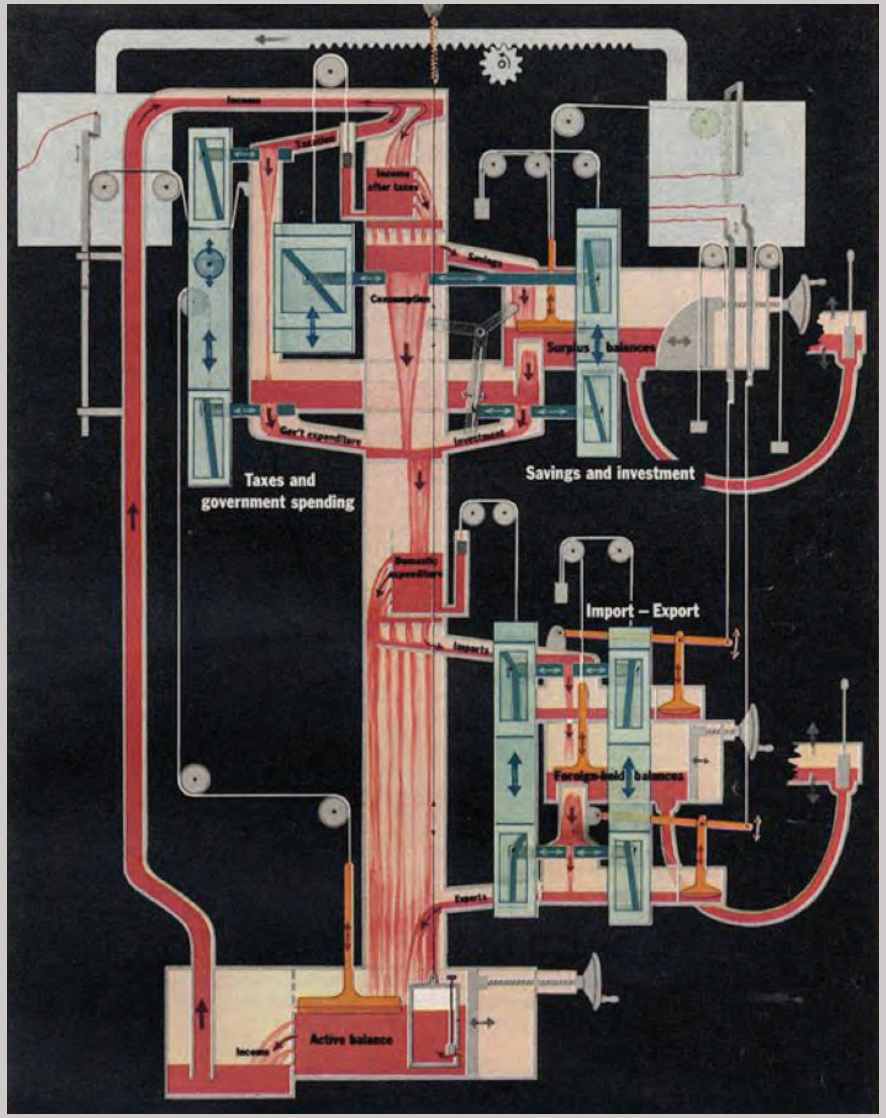


Diagram of the Phillips machine. Source: LSE Quarterly, Winter 1988, Nick Barr.

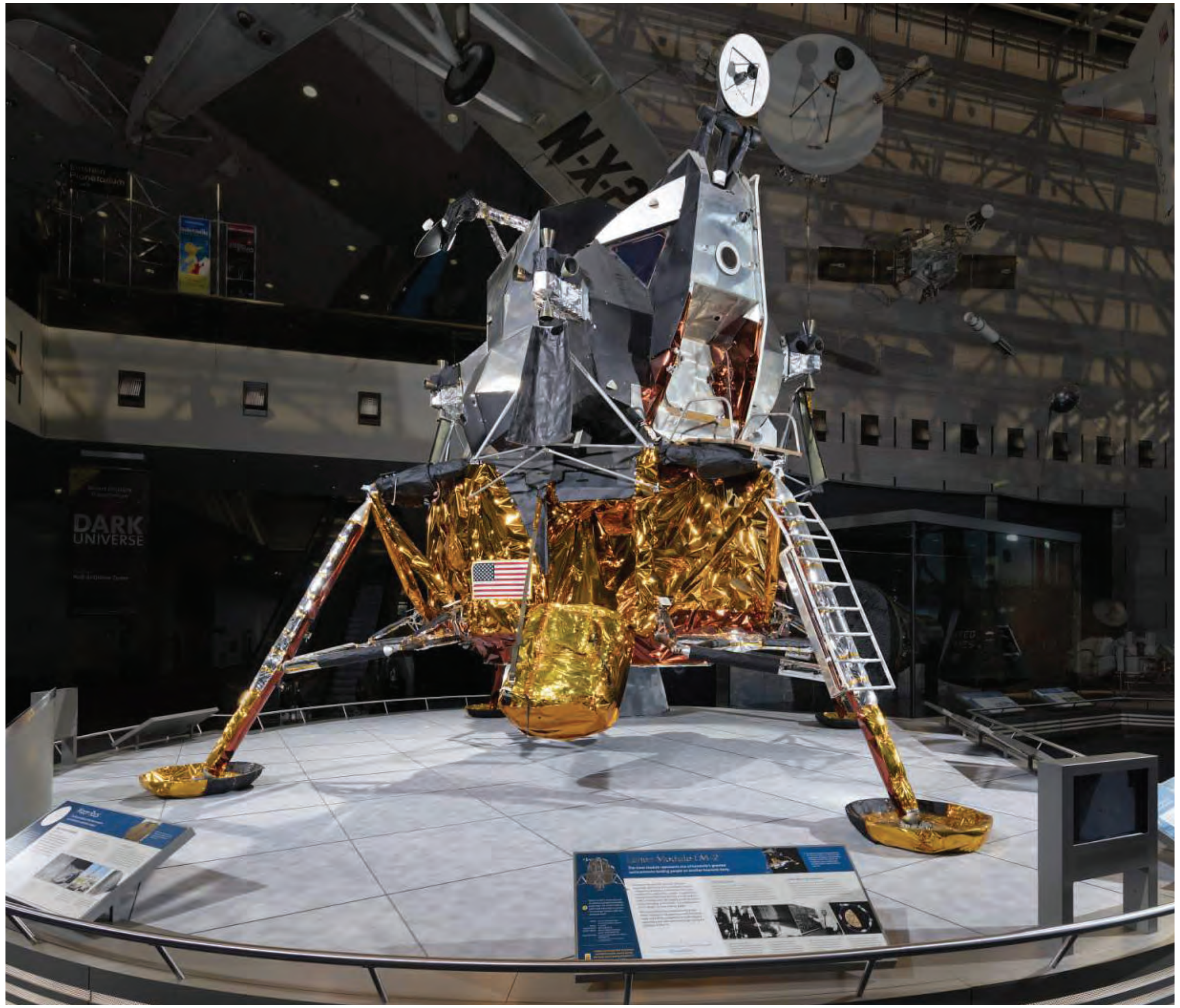


U.S. Army Corps of Engineers Bay Model

Built in 1957

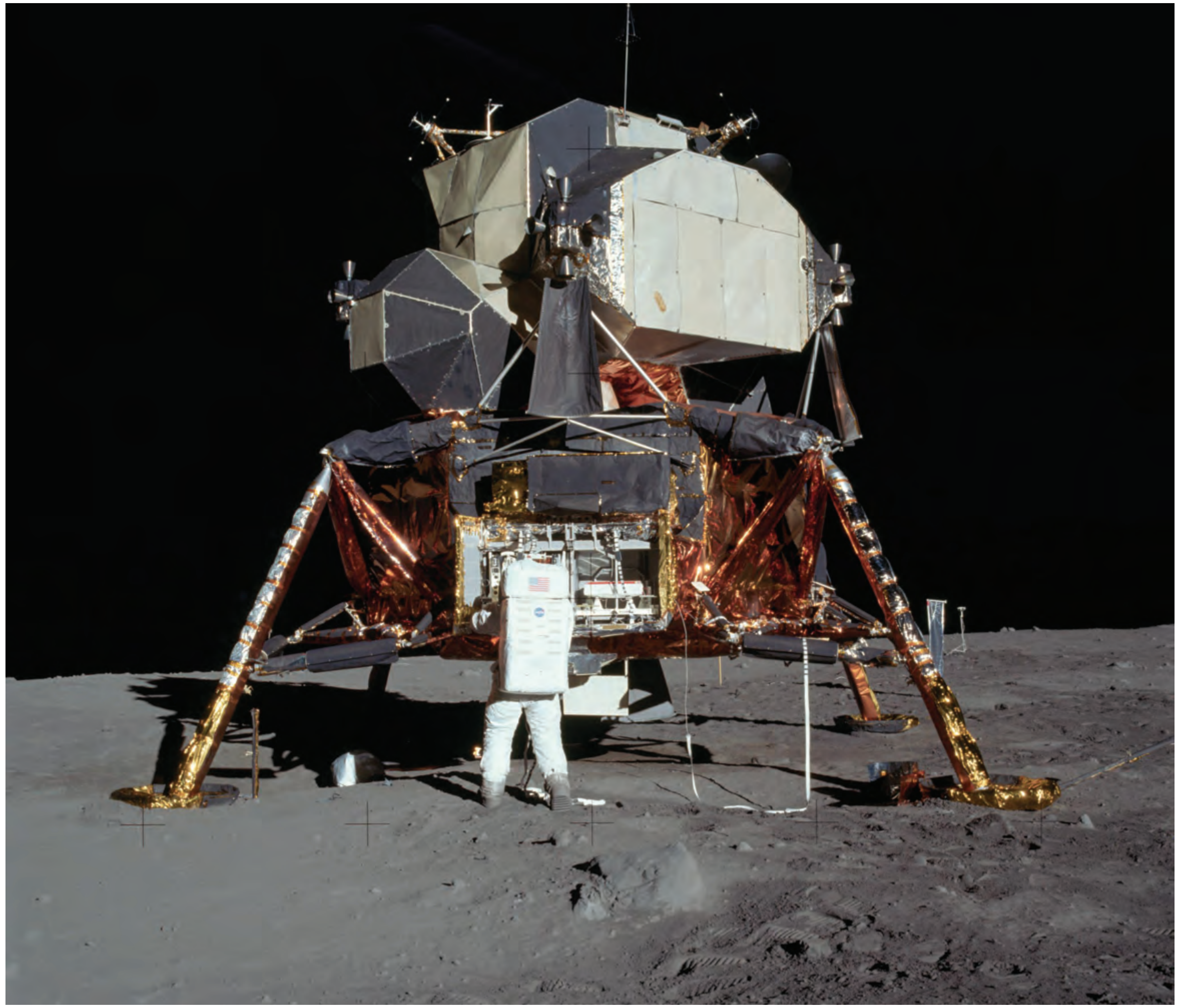
Lunar module #2

Used for ground testing



Lunar module #5, “Eagle”

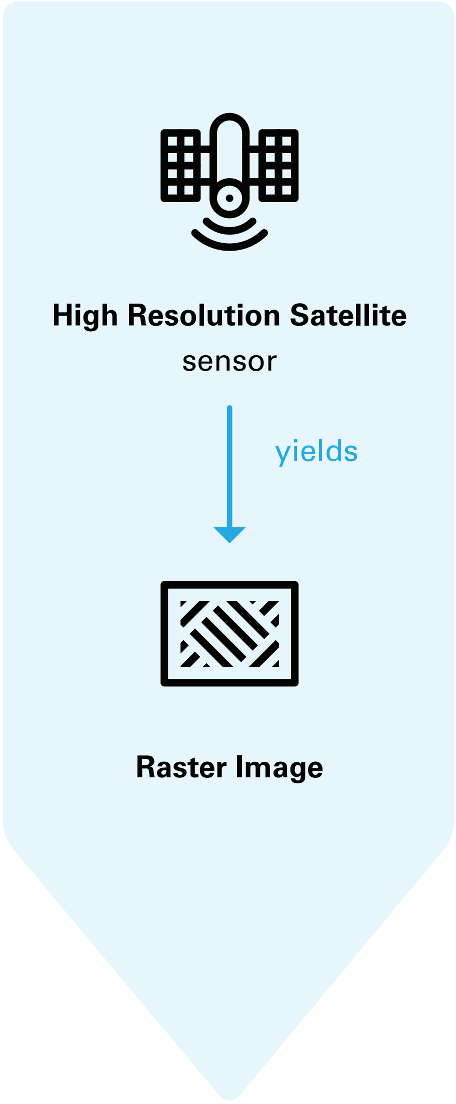
Apollo 11 (landed July 21, 1969)

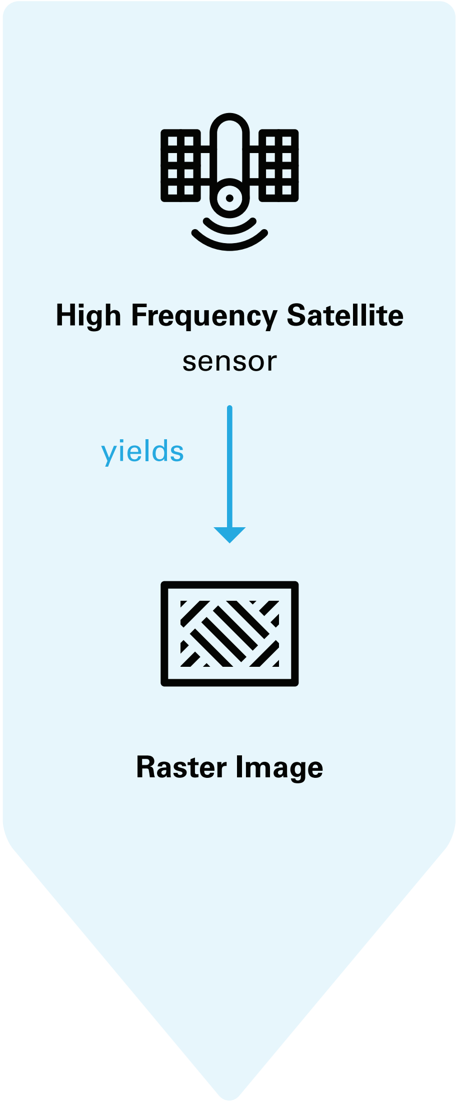


Additional slides

Data is available as reusable building blocks

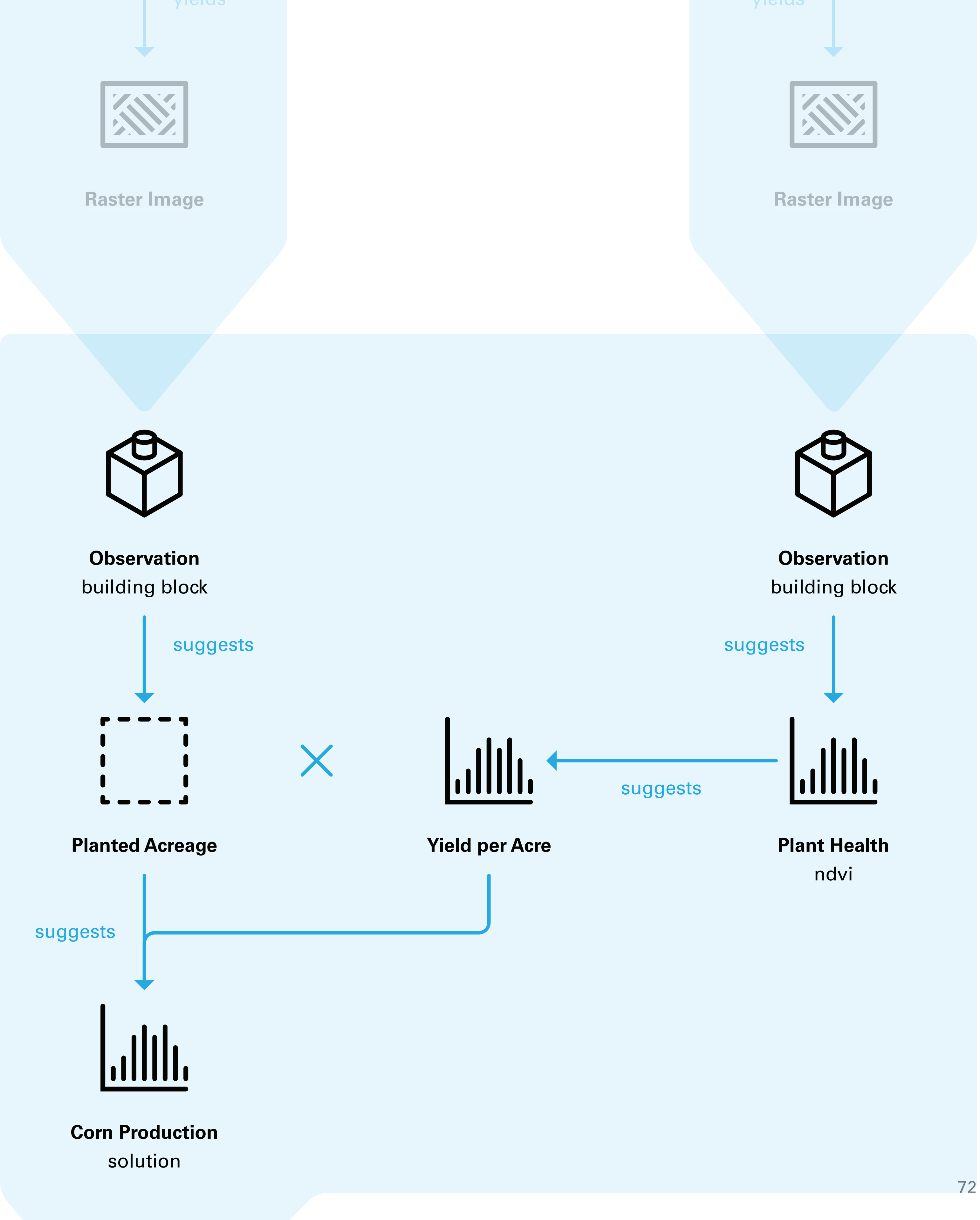
They can be assembled to form a “solution”— a way to answer a question. Blocks vary from raster to vector, from “raw” to highly refined.





Assemble building blocks to find the answers that matter.

Solutions are structured as a graph, where building blocks are nodes, and operations are edges.



Infinitely nest solutions to tackle even the hardest problems.

Solutions are building blocks too, available for use in other solutions.