Introduction to Cyber-Physical Systems (CPS)

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CPS: Computing Perspective

- **Two types of computing systems**
  - Desktops, servers, PCs, and notebooks
  - Embedded
- **The next frontier**
  - Mainframe computing (60's-70's)
    - Large computers to execute big data processing applications
  - Desktop computing & Internet (80's-90's)
    - One computer at every desk to do business/personal activities
  - **Embedded computing (21st Century)**
    - **"Invisible" part of the environment**
    - **Transformation of industry**

- **Number of microprocessor units per year**
  - Millions in desktops
  - Billions in embedded processors
- **Applications:**
  - Automotive Systems
    - Light and heavy automobiles, trucks, buses
  - Aerospace Systems
    - Airplanes, space systems
  - Consumer electronics
    - Mobile phones, office electronics, digital appliances
  - Health/Medical Equipment
    - Patient monitoring, MRI, infusion pumps, artificial organs
  - Industrial Automation
    - Supervisory Control and Data Acquisition (SCADA) systems for chemical and power plants
    - Manufacturing systems
  - Defense
    - Source of superiority in all weapon systems

CPS: Systems Perspective

Sectors	**Opportunities**	
Transportation	Aircraft that fly faster and further on less energy. Air traffic control systems that make more efficient use of airspace. Automobiles that are more capable and safer but use less energy.	
Defense	More capable defense systems; defense systems that make better use of networked fleets of autonomous vehicles.	
Energy and Industrial Automation	New and renewable energy sources. Homes, office, buildings and vehicles that are more energy efficient and cheaper to operate.	

What are Cyber-Physical Systems?

Deeply integrating computation, communication, and control into physical systems

Characteristics of CPS

- Pervasive computation, sensing and control
- Networked at multi- and extreme scales
- Dynamically reorganizing/reconfiguring
- High degrees of automation
- Dependable operation with *potential* requirements for high assurance of reliability, safety, security and usability
- With / without human in on-the-loop
- Conventional and unconventional substrates / platforms
- Ranges from the very small – BioCPS (DNA and Micro-robots) to the large (Boeing 787 / Airbus 380) to the very large (city scale)

Application Domains

Transportation

- Faster and safer vehicles (airplanes, cars, etc)
- Improved use of airspace and roadways
- Energy efficiency
- Manned and un-manned

Energy and Industrial Automation

- Homes and offices that are more energy efficient and cheaper to operate
- Distributed micro-generation for the grid

Healthcare and Biomedical

- Increased use of effective in-home care
- More capable devices for diagnosis
- New internal and external prosthetics

Critical Infrastructure

- More reliable power grid
- Highways that allow denser traffic with increased safety

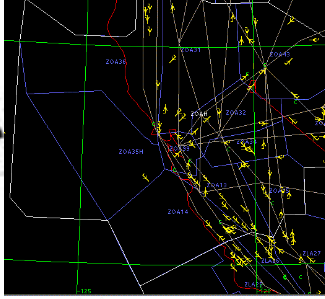
CPS Definition

A CPS is a system in which:

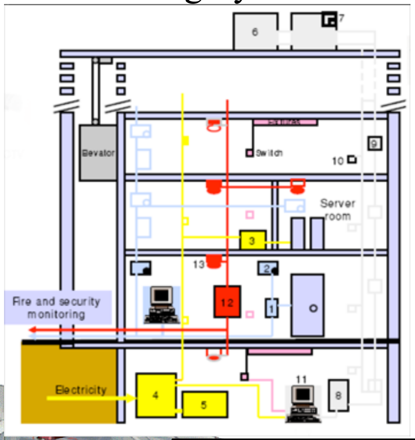
- information processing and physical processes are so tightly integrated that it is not possible to identify whether behaviors are the result of computations, physical laws, or both working together
- where functionality and salient system characteristics are emerging through the interaction of physical and computational objects

Cyber-Physical Systems (CPS):
Orchestrating networked computational resources with physical systems

Avionics

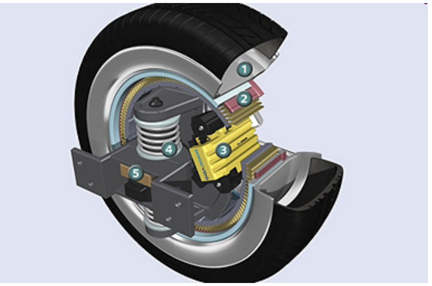


Building Systems

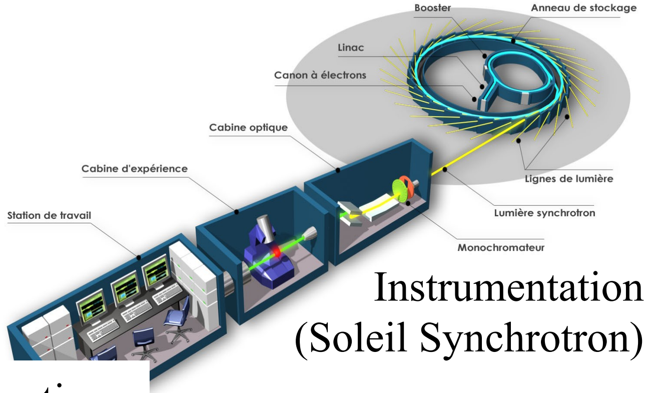


Telecommunications

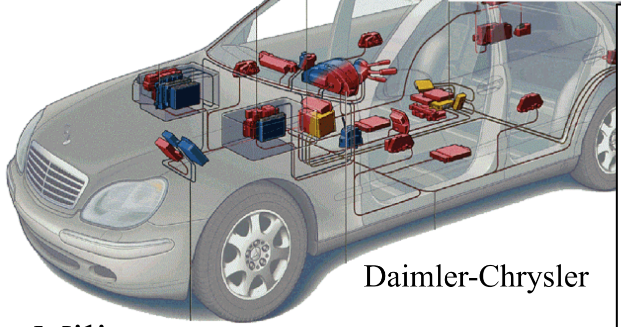
Automotive



E-Corner, Siemens



Instrumentation (Soleil Synchrotron)



Daimler-Chrysler

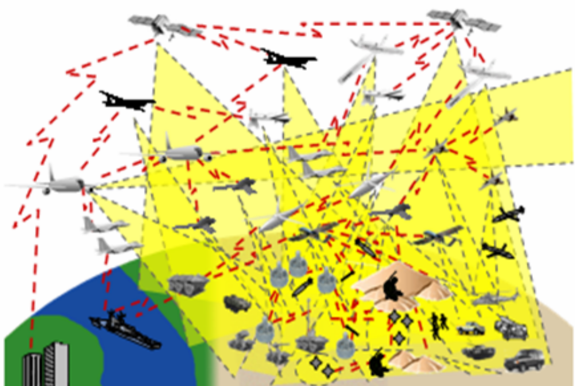
Power generation and distribution

Courtesy of General Electric

Factory automation

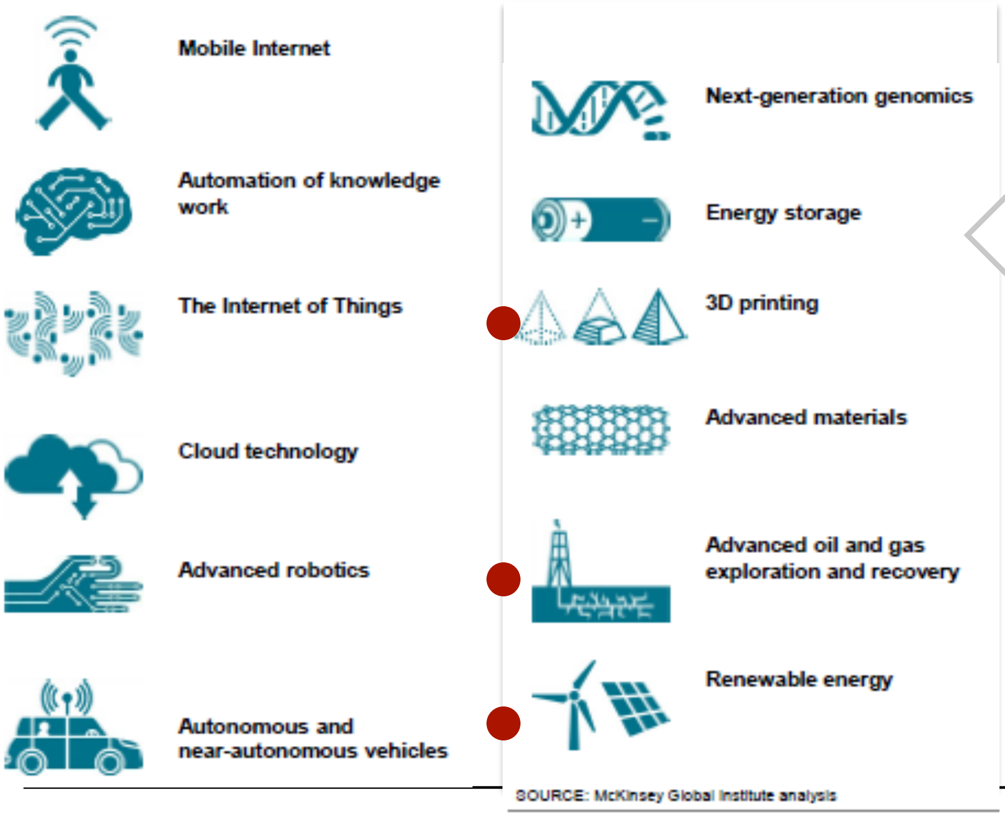
Courtesy of Kuka Robotics Corp.

Military systems:



CPS is a big part of "The Future" (according to McKinsey)…

Top twelve economically disruptive technologies (by 2025)



- ● Mobile Internet
- ● Automation of knowledge work
- ● The Internet of Things
- ● Cloud technology
- ● Advanced robotics
- ● Autonomous and near-autonomous vehicles
- Next-generation genomics
- Energy storage
- ● 3D printing
- Advanced materials
- ● Advanced oil and gas exploration and recovery
- ● Renewable energy

SOURCE: McKinsey Global Institute analysis

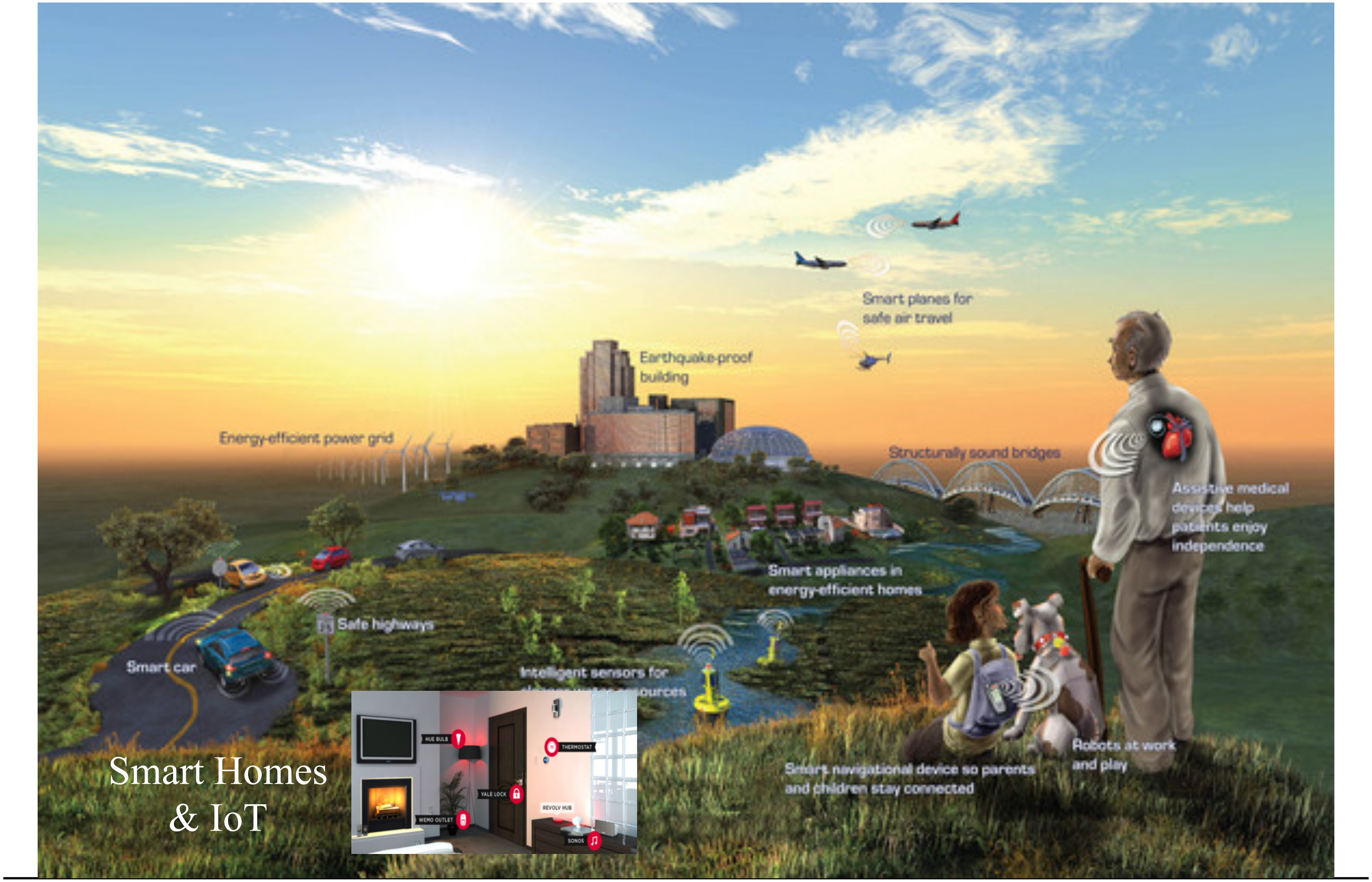
McKinsey&Company

McKinsey Global Institute

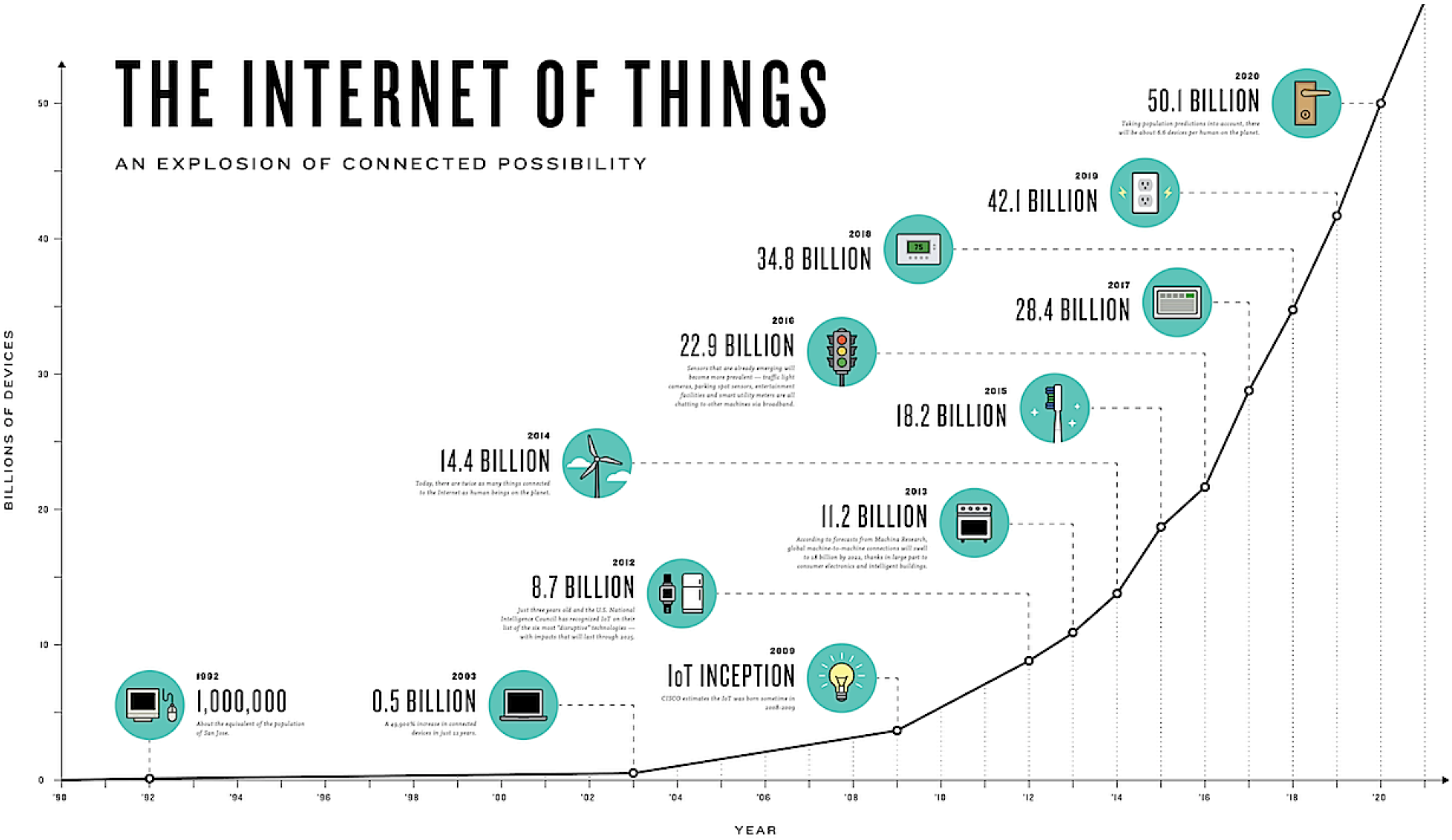
May 2013

Disruptive technologies: Advances that will transform life, business, and the global economy

CPS Research is Fundamental to Smart and Connected Communities and Internet of Things

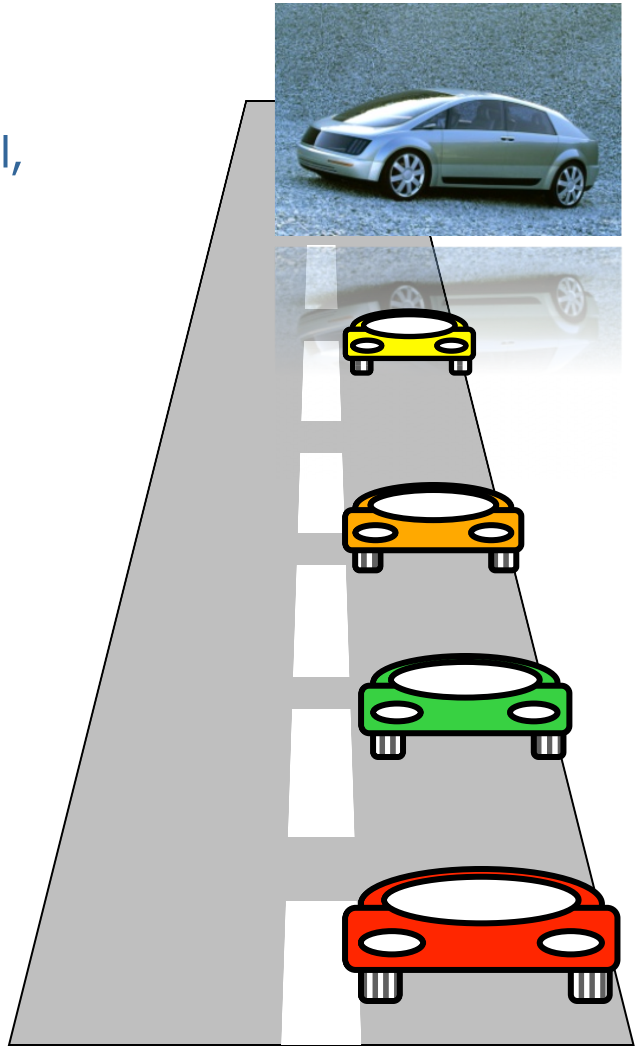

Smart planes for safe air travel
Earthquake-proof building
Energy-efficient power grid
Structurally sound bridges
Assistive medical devices help patients enjoy independence
Smart appliances in energy-efficient homes
Safe highways
Smart car
Intelligent sensors for
Robots at work and play
Smart navigational device so parents and children stay connected
HUE BULB
THERMOSTAT
YALE LOCK
REVOLV HUB
WEMO OUTLET
SONOS

Smart Homes & IoT


THE INTERNET OF THINGS
AN EXPLOSION OF CONNECTED POSSIBILITY
BILLIONS OF DEVICES
50
40
30
20
10
0
1992
1,000,000
About the equivalent of the population of San Jose.
2003
0.5 BILLION
A 49,900% increase in connected devices in just 11 years.
2009
IoT INCEPTION
CISCO estimates the IoT was born sometime in 2008-2009
2012
8.7 BILLION
Just three years old and the U.S. National Intelligence Council has recognized IoT on their list of the six most "disruptive" technologies — with impacts that will last through 2025.
2013
11.2 BILLION
According to forecasts from Machina Research, global machine-to-machine connections will swell to 18 billion by 2022, thanks in large part to consumer electronics and intelligent buildings.
2014
14.4 BILLION
Today, there are twice as many things connected to the Internet as human beings on the planet.
2015
18.2 BILLION
2016
22.9 BILLION
Sensors that are already emerging will become more prevalent — traffic light cameras, parking spot sensors, entertainment facilities and smart utility meters are all chatting to other machines via broadband.
2017
28.4 BILLION
2018
34.8 BILLION
75
2019
42.1 BILLION
2020
50.1 BILLION
Taking population predictions into account, there will be about 6.6 devices per human on the planet.
'90
'92
'94
'96
'98
'00
'02
'04
'06
'08
'10
'12
'14
'16
'18
'20
YEAR

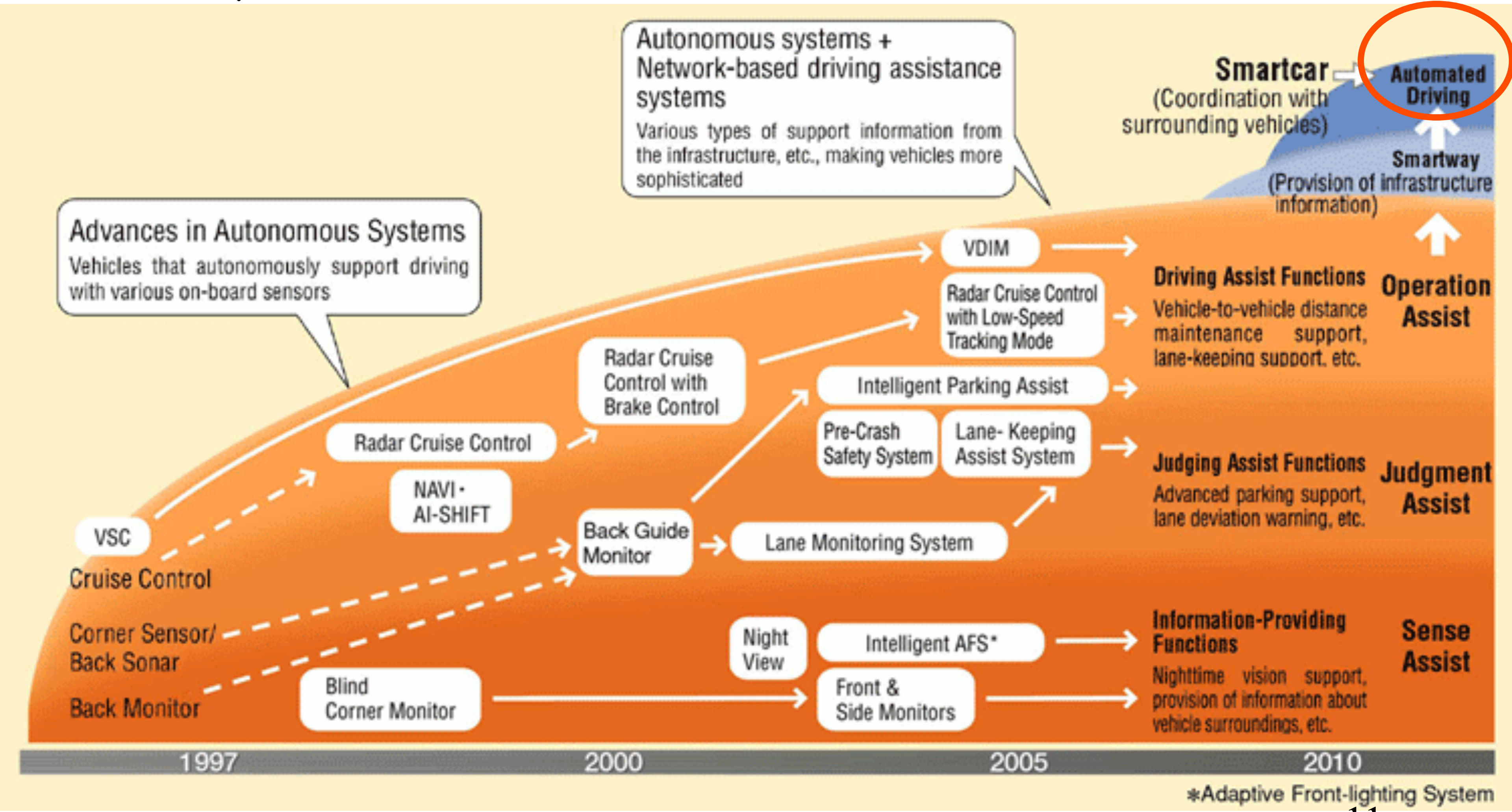
Transformation of Industries: Automotive

- **Current picture**
  - Largely single-vehicle focus
  - Integrating safety and fuel economy (full hybrids, regenerative braking, adaptive transmission control, stability control)
  - Safety and convenience "add-ons" (collision avoidance radar, complex airbag systems, GPS, …)
  - Cost of recalls, liability; growing safety culture
- **Better future?**
  - Multi-vehicle high-capacity cooperative control roadway technologies
  - Vehicular networks
  - Energy-absorbing "smart materials" for collision protection (cooperative crush zones?)
  - Alternative fuel technologies, "smart skin" integrated photovoltaics and energy scavaging, ….
  - Integrated operation of drivetrain, smart tires, active aerodynamic surfaces, …
  - Safety, security, privacy certification; regulatory enforcement
- **Time-to-market race**



Example: Toyota autonomous vehicle technology roadmap

Source: Toyota Web site


Autonomous systems + Network-based driving assistance systems
Various types of support information from the infrastructure, etc., making vehicles more sophisticated
Smartcar
(Coordination with surrounding vehicles)
Automated Driving
Smartway
(Provision of infrastructure information)
Advances in Autonomous Systems
Vehicles that autonomously support driving with various on-board sensors
VDIM
Radar Cruise Control with Low-Speed Tracking Mode
Driving Assist Functions
Vehicle-to-vehicle distance maintenance support, lane-keeping support, etc.
Operation Assist
Radar Cruise Control with Brake Control
Intelligent Parking Assist
Radar Cruise Control
Pre-Crash Safety System
Lane- Keeping Assist System
Judging Assist Functions
Advanced parking support, lane deviation warning, etc.
Judgment Assist
NAVI・AI-SHIFT
VSC
Back Guide Monitor
Lane Monitoring System
Cruise Control
Corner Sensor/ Back Sonar
Back Monitor
Night View
Intelligent AFS*
Information-Providing Functions
Nighttime vision support, provision of information about vehicle surroundings, etc.
Sense Assist
Blind Corner Monitor
Front & Side Monitors
1997
2000
2005
2010
*Adaptive Front-lighting System

Transformation of Industries: Health Care and Medicine

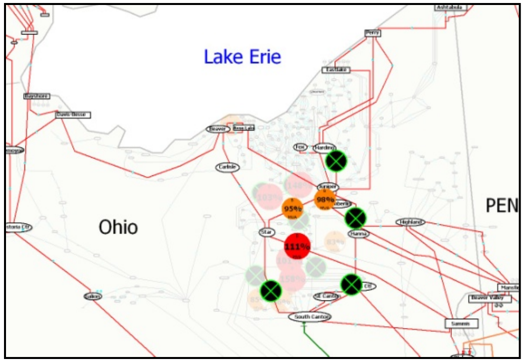
- **National Health Information Network, Electronic Patient Record initiative**
  - Medical records at any point of service
  - Hospital, OR, ICU, …, EMT?
- **Home care: monitoring and control**
  - Pulse oximeters (oxygen saturation), blood glucose monitors, infusion pumps (insulin), accelerometers (falling, immobility), wearable networks (gait analysis), …

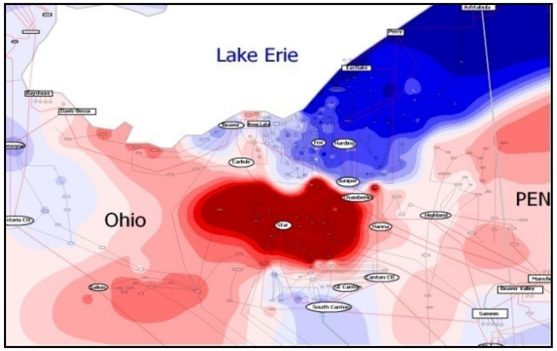
- **Operating Room of the Future (Goldman)**
  - Closed loop monitoring and control; multiple treatment stations, plug and play devices; robotic microsurgery (remotely guided?)
  - System coordination challenge
- **Progress in bioinformatics: gene, protein expression; systems biology; disease dynamics, control mechanisms**

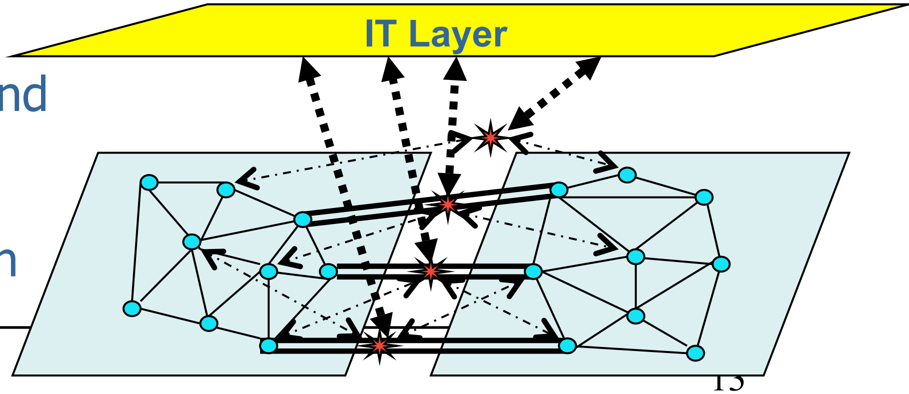
Images thanks to Dr. Julian Goldman, Dr. Fred Pearce

Transformation of Industries: Electric Power Grid

- **Current picture:**
  - Equipment protection devices trip locally, reactively
  - Cascading failure: August (US/Canada) and October (Europe), 2003
- **Better future?**
  - Real-time cooperative control of protection devices
  - Or -- self-healing -- (re-)aggregate islands of stable bulk power (protection, market motives)
  - Ubiquitous green technologies
  - Issue: standard operational control concerns exhibit wide-area characteristics (bulk power stability and quality, flow control, fault isolation)
  - Context: market (timing?) behavior, power routing transactions, regulation

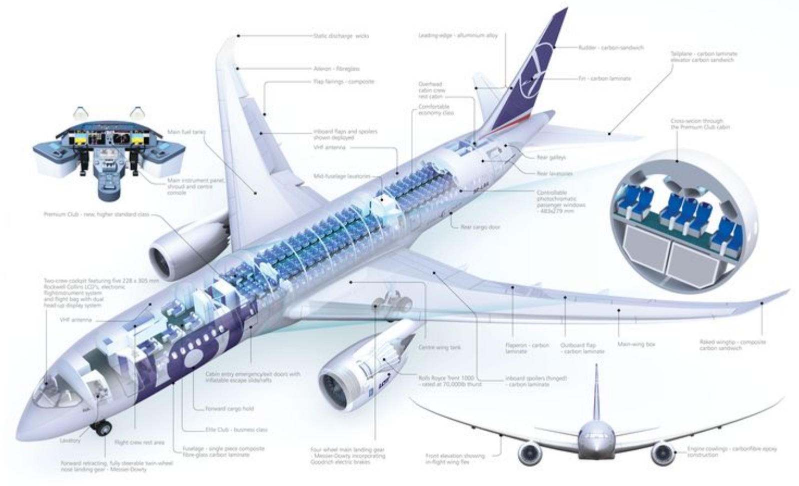






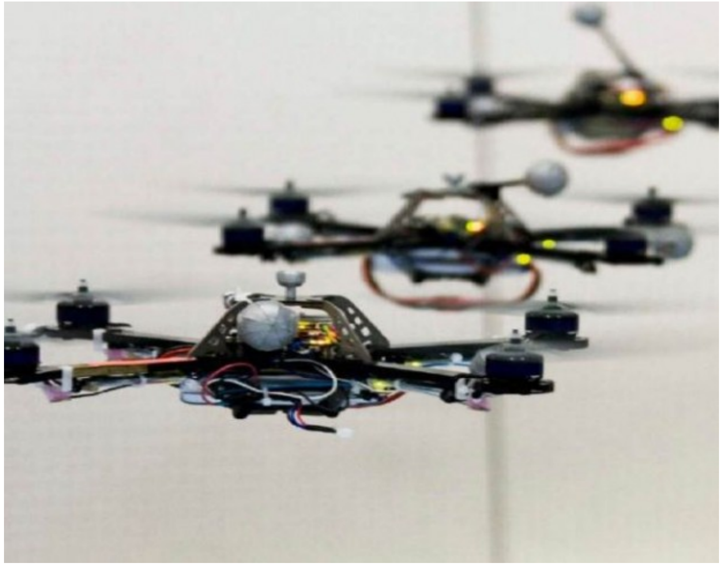
Images thanks to William H. Sanders, Bruce Krogh, and Marija Ilic

Transformation of Industries: Manned and Unmanned Aerial Vehicles

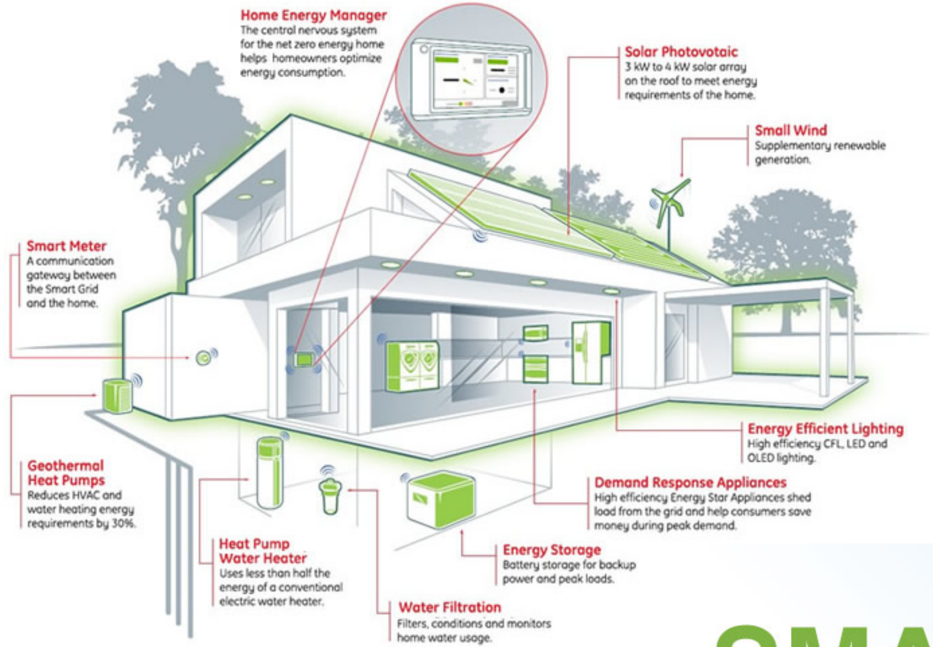

Static discharge wicks
Leading-edge - alluminium alloy
Rudder - carbon-sandwich
Tailplane - carbon laminate elevator carbon sandwich
Aileron - fibreglass
Flap fairings - composite
Fin - carbon laminate
Overhead cabin crew rest cabin
Comfortable economy class
Main fuel tanks
Inboard flaps and spoilers shown deployed
VHF antenna
Cross-section through the Premium Club cabin
Rear galleys
Rear lavatories
Main instrument panel, shroud and centre console
Mid-fuselage lavatories
Controllable photochromatic passenger windows - 483x279 mm
Premium Club - new, higher standard class
Rear cargo door
Two-crew cockpit featuring five 228 x 305 mm Rockwell Collins LCD's, electronic flightinstrument system and flight bag with dual head-up display system
VHF antenna
Centre wing tank
Flaperon - carbon laminate
Outboard flap - carbon laminate
Main-wing box
Raked wingtip - composite carbon sandwich
Cabin entry emergency/exit doors with inflatable escape slide/rafts
Rolls Royce Trent 1000 - rated at 70,000lb thrust
Inboard spoilers (hinged) - carbon laminate
Forward cargo hold
Elite Club - business class
Lavatory
Flight crew rest area
Fuselage - single piece composite fibre-glass carbon laminate
Four wheel main landing gear - Messier-Dowty incorporating Goodrich electric brakes
Front elevation showing in-flight wing flex
Engine cowlings - carbonfibre epoxy construction
Forward retracting, fully steerable twin-wheel nose landing gear - Messier-Dowty

Google, Amazon, and Walmart want to deliver products to your doorstep nearly instantly by using drones

- Dreamliner
  - ~1330 networked microprocessors
  - 50% of design cost ($ and time)
  - Correctness of software challenge
  - Cybersecurity (i.e., GPS spoofing)



Transformation of Industries: Smart Buildings



Home Energy Manager
The central nervous system for the net zero energy home helps homeowners optimize energy consumption.

Solar Photovotaic
3 kW to 4 kW solar array on the roof to meet energy requirements of the home.

Small Wind
Supplementary renewable generation.

Smart Meter
A communication gateway between the Smart Grid and the home.

Energy Efficient Lighting
High efficiency CFL, LED and OLED lighting.

Geothermal Heat Pumps
Reduces HVAC and water heating energy requirements by 30%.

Demand Response Appliances
High efficiency Energy Star Appliances shed load from the grid and help consumers save money during peak demand.

Heat Pump Water Heater
Uses less than half the energy of a conventional electric water heater.

Energy Storage
Battery storage for backup power and peak loads.

Water Filtration
Filters, conditions and monitors home water usage.

SMART BUILDINGS

An Intelligent Business Proposition

The structures that dot the skyline aren't just concrete and glass, static shells. It's time to put buildings to work. Make it easy for students to find the library on campus. (No more excuses.) Uncover new revenue streams in real estate.

Get green, safe and productive.

In a few words…

Cyber-physical systems are smart, complete systems of tomorrow;

Cyber-physical systems will enable ubiquitous technologies and applications for the future.

Advances in *cyber-physical systems* will reshape our world with more responsive, secure, and efficient systems that:

- ***Transform*** the way we live
- ***Drive*** economic prosperity
- ***Underpin*** national security
- ***Enhance*** societal well-being
- Users depend on and may ***bet their life on***

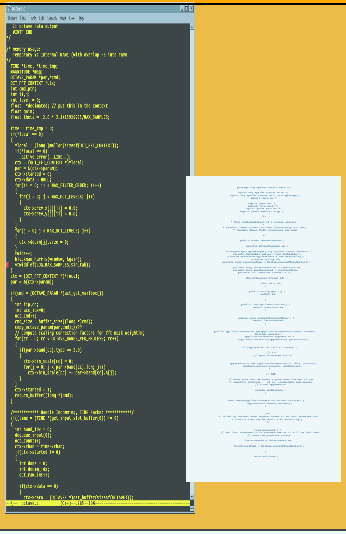
Long-Term Goal

- **Transform how we interact with the physical world** just like the internet transformed how we interact with one another.
  - Transcend space
  - Control the physical environment remotely
- Building CPS that integrate computational and physical objects requires **new systems science foundations**.
  - Fusion of physical and computational sciences

Produce significant impact on society and national competitiveness.

Why is CPS Hard?

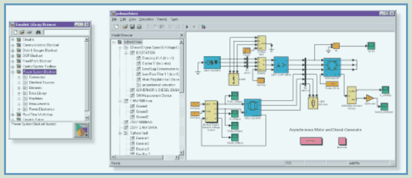
Software

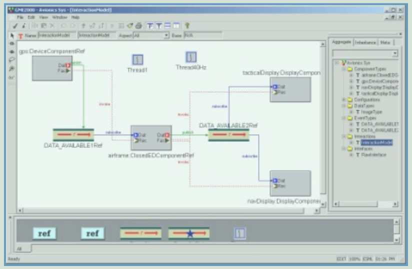


octave.c

```
  2: octave data output
  #INTF_END
*/

/* memory usage:
  Temporary Y: Internal RAM1 (with overlap -8 into ram0
*/
  TIME *time, *time_tmp;
  MAGNITUDE *mag;
  OCTAVE_PARAM *par,*cmd;
  OCT_FFT_CONTEXT *ctx;
  int cmd_ptr;
  int ii,j;
  int level = 0;
  float  *decimated; // put this in the context
  float gain;
  float theta =  2.0 * 3.1415926535/MAX_SAMPLES;

  time = time_tmp = 0;
  if(*local == 0)
  {
    *local = (long )malloc(sizeof(OCT_FFT_CONTEXT));
    if(*local == 0)
      _active_error(__LINE__);
    ctx = (OCT_FFT_CONTEXT *)*local;
    par = &(ctx->param);
    ctx->started = 0;
    ctx->data = NULL;
    for(ii = 0; ii < MAX_FILTER_ORDER; ii++)
    {
      for(j = 0; j < MAX_OCT_LEVELS; j++)
      {
        ctx->prev_x[j][ii] = 0.0;
        ctx->prev_y[j][ii] = 0.0;
      }
    }
    for(j = 0; j < MAX_OCT_LEVELS; j++)
    {
      ctx->decim[j].size = 0;
    }
    twids++;
    blackman_harris(window, &gain);
    vtwiddlef(LOG_MAX_SAMPLES,sin_tab);
  }
  ctx = (OCT_FFT_CONTEXT *)*local;
  par = &(ctx->param);

  if(cmd = (OCTAVE_PARAM *)act_get_mailbox())
  {
    int iip,cc;
    int acc_idx=0;
    oct_cmd++;
    cmd_size = buffer_size((long *)cmd);
    copy_octave_param(par,cmd);//??
    // compute scaling correction factors for fft mask weighting
    for(cc = 0; cc < OCTAVE_BANDS_PER_PROCESS; cc++)
    {
      if(par->band[cc].type == 2.0)
      {
        ctx->bin_scale[cc] = 0;
        for(j = 0; j < par->band[cc].len; j++)
          ctx->bin_scale[cc] += par->band[cc].A[j];
      }
    }
    ctx->started = 1;
    return_buffer((long *)cmd);
  }

  /************ Handle Incomming, TIME Packet ************/
  if((time = (TIME *)get_input_slot_buffer(0)) != 0)
  {
    int band_idx = 0;
    dequeue_input(0);
    oct_count++;
    ctx->chan = time->chan;
    if(ctx->started != 0)
    {
      int done = 0;
      int decim_idx;
      oct_raw_ins++;

      if(ctx->data == 0)
      {
        ctx->data = (OCTAVE3 *)get_buffer(sizeof(OCTAVE3));
--\--  octave.c        (C++)--L285--39%------------------------------------
```

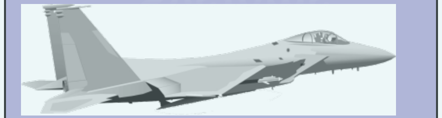
Control

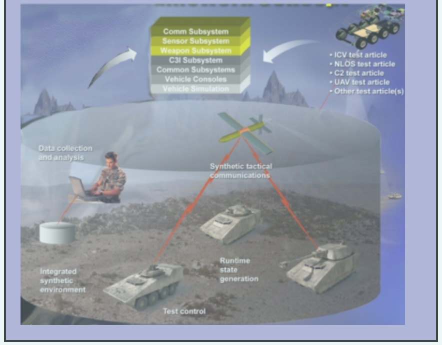




gps DeviceComponentRef
Thread1
Thread40Hz
tacticalDisplay.DisplayComponent
DATA_AVAILABLE1Ref
DATA_AVAILABLE2Ref
airframe ClosedEDComponentRef
navDisplay.DisplayComponent
ref
ref

Systems

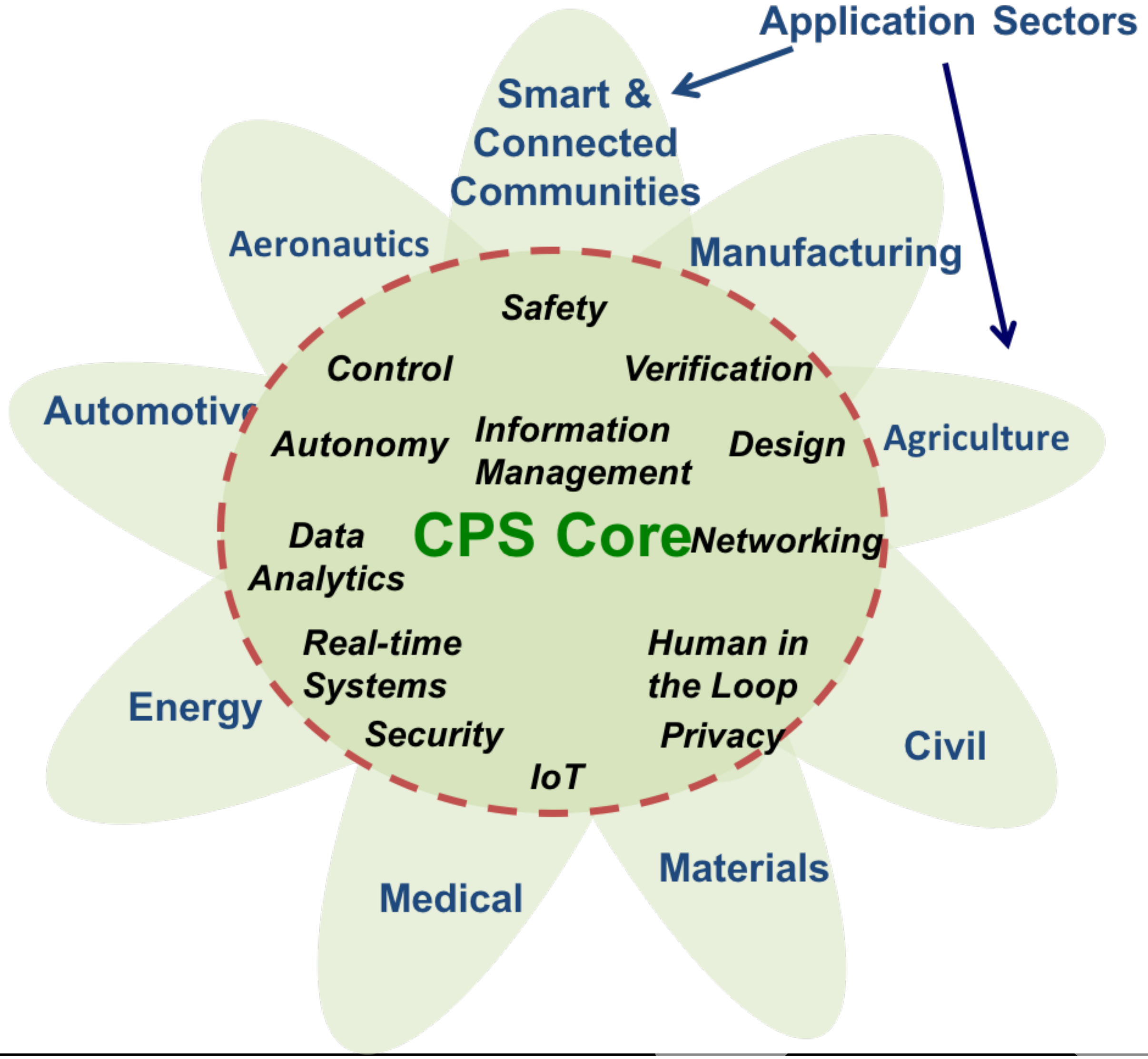




Crosses Interdisciplinary Boundaries

- **Disciplinary boundaries need to be realigned**
- **New fundamentals need to be created**
- **New technologies and tools need to be developed**
- **Education need to be restructured**

National Science Foundation



Software: The Great Enabler

- Good news: anything is possible in software!
- Bad news: anything is possible in software!

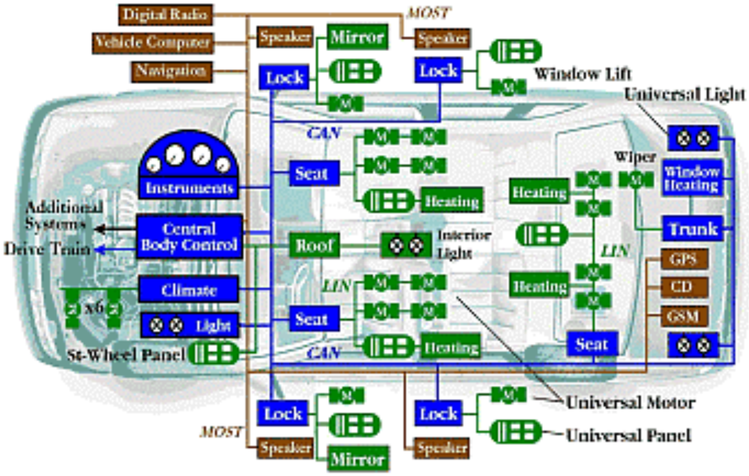
- It is the software that affects system complexity and also cost.
  - Software development stands for 70-80% of the overall development cost for some embedded systems.

Ariane 5 Explosion

"It took the European Space Agency 10 years and $7 billion to produce Ariane 5. All it took to explode that rocket less than a minute into its maiden voyage last June, scattering fiery rubble across the mangrove swamps of French Guiana, was a small computer program trying to stuff a 64-bit number into a 16-bit space"

A bug and a crash, J. Gleick, New York Times, Dec 1996

Prius Brake Problems Blamed on Software Glitches



“Toyota officials described the problem as a "disconnect" in the vehicle's complex anti-lock brake system (ABS) that causes less than a one-second lag. With the delay, a vehicle going 60 mph will have traveled nearly another 90 feet before the brakes begin to take hold”

CNN Feb 4, 2010

Auto Recalls

- **1.5M** (in US) Honda Accord, CR-V and Element vehicles recalled “to update the software that controls their automatic transmissions”

- **~75K** Toyota Hybrids recalled for “could enter a "fail-safe" mode that shuts down the engine, allowing only limited operation using the electric motor. The problem, caused by a software error in the Electronic Control Module (ECM) system, triggers up to five warning lights while shutting down the engine.”

Software: The Achilles' Heel

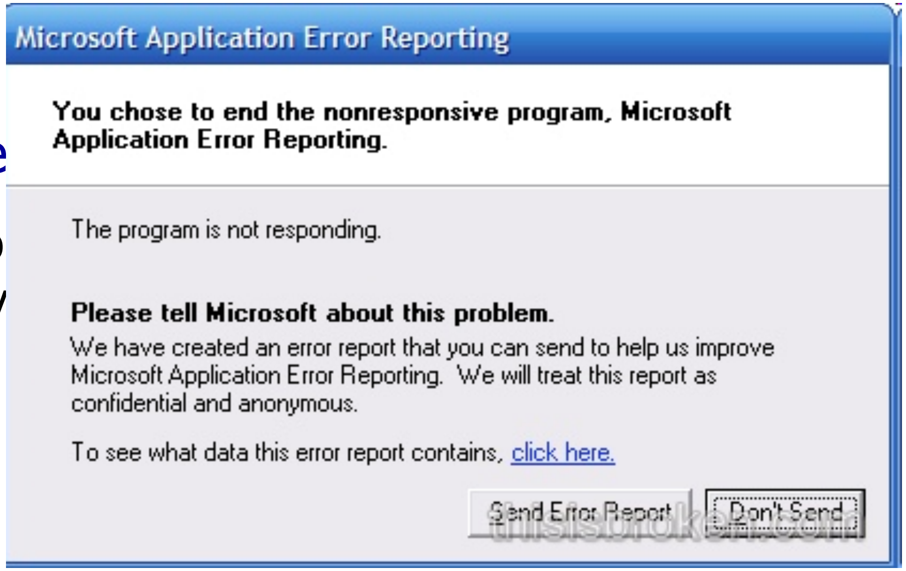
Software everywhere means bugs everywhere

2002 study by NIST:

Software bugs cost US economy $60 billion annually (0.6% of GDP)

Lack of trust in software as te

Would you use an autono
monitoring and drug-deliv



Microsoft Application Error Reporting

You chose to end the nonresponsive program, Microsoft Application Error Reporting.

The program is not responding.

Please tell Microsoft about this problem.

We have created an error report that you can send to help us improve Microsoft Application Error Reporting. We will treat this report as confidential and anonymous.

To see what data this error report contains, click here.

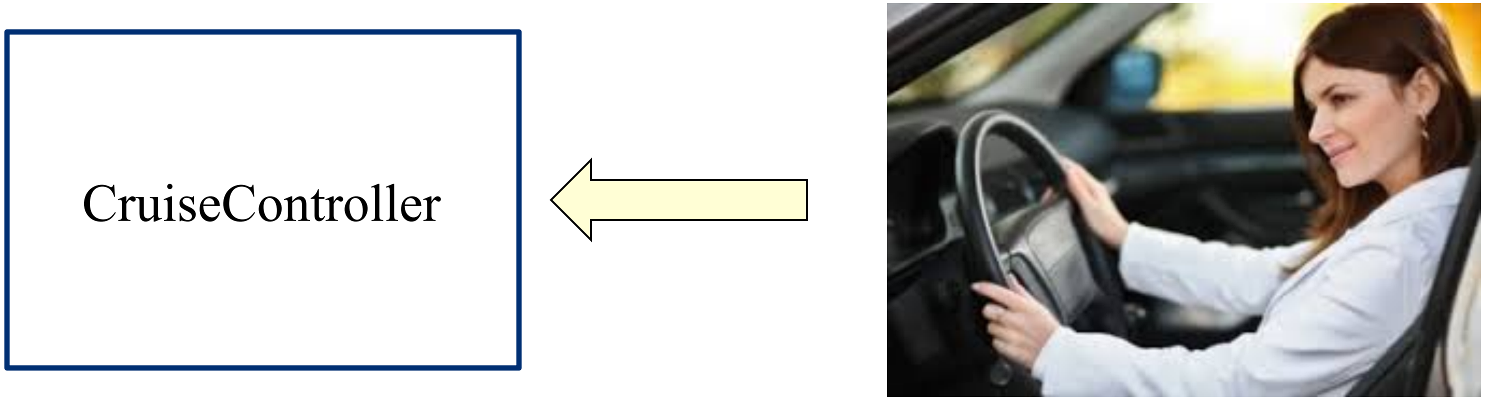
Grand challenge:
Technology for designing dependable cyber-physical systems

Let's Design a Cruise Controller

What's the goal of a cruise controller?

Automatically adjust the speed of the car so that it matches the speed desired by the driver

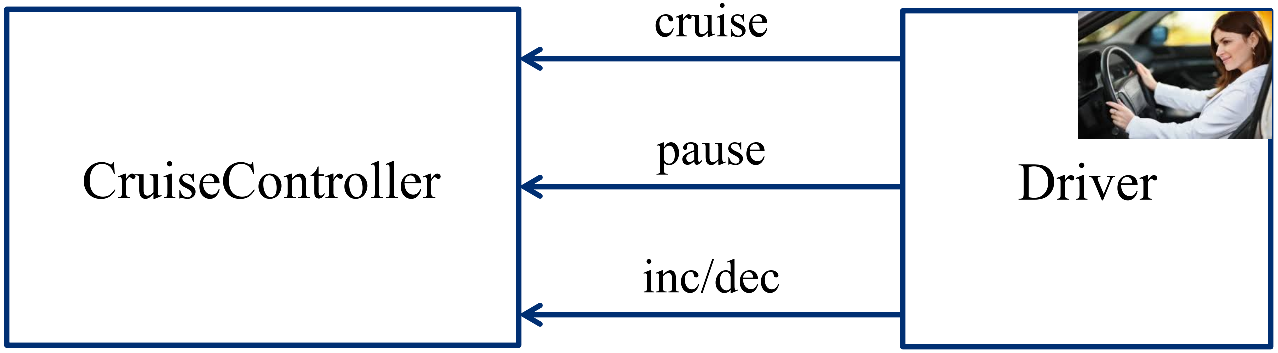
Block Diagrams of High-Level Design



CruiseController

How does this component interact with the rest of the world ?

Interfaces for Components: Inputs and Outputs



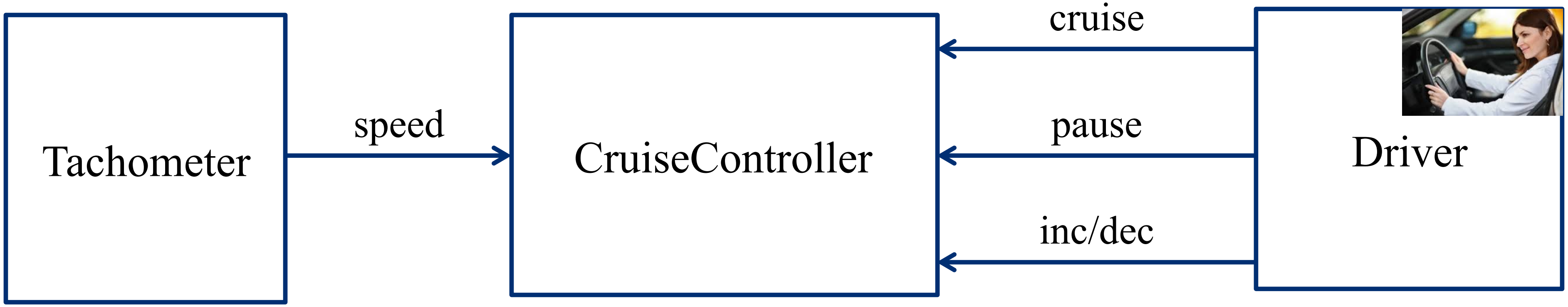
Driver interacts with the system using 4 buttons:

Cruise button to turn the cruise on or off

Pause button to suspend/restart its operation

Inc and Dec buttons to increment or decrement desired speed

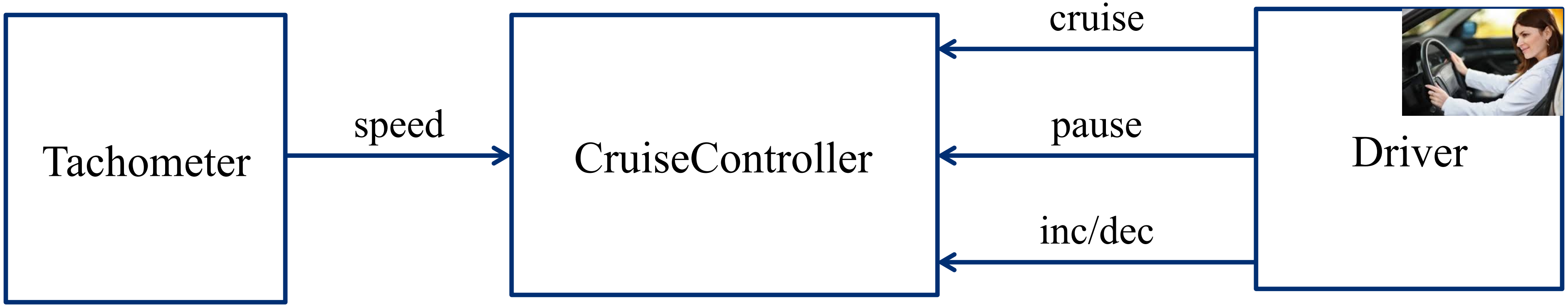
Interfaces for Components: Inputs and Outputs



What other information does the cruise-controller need ?

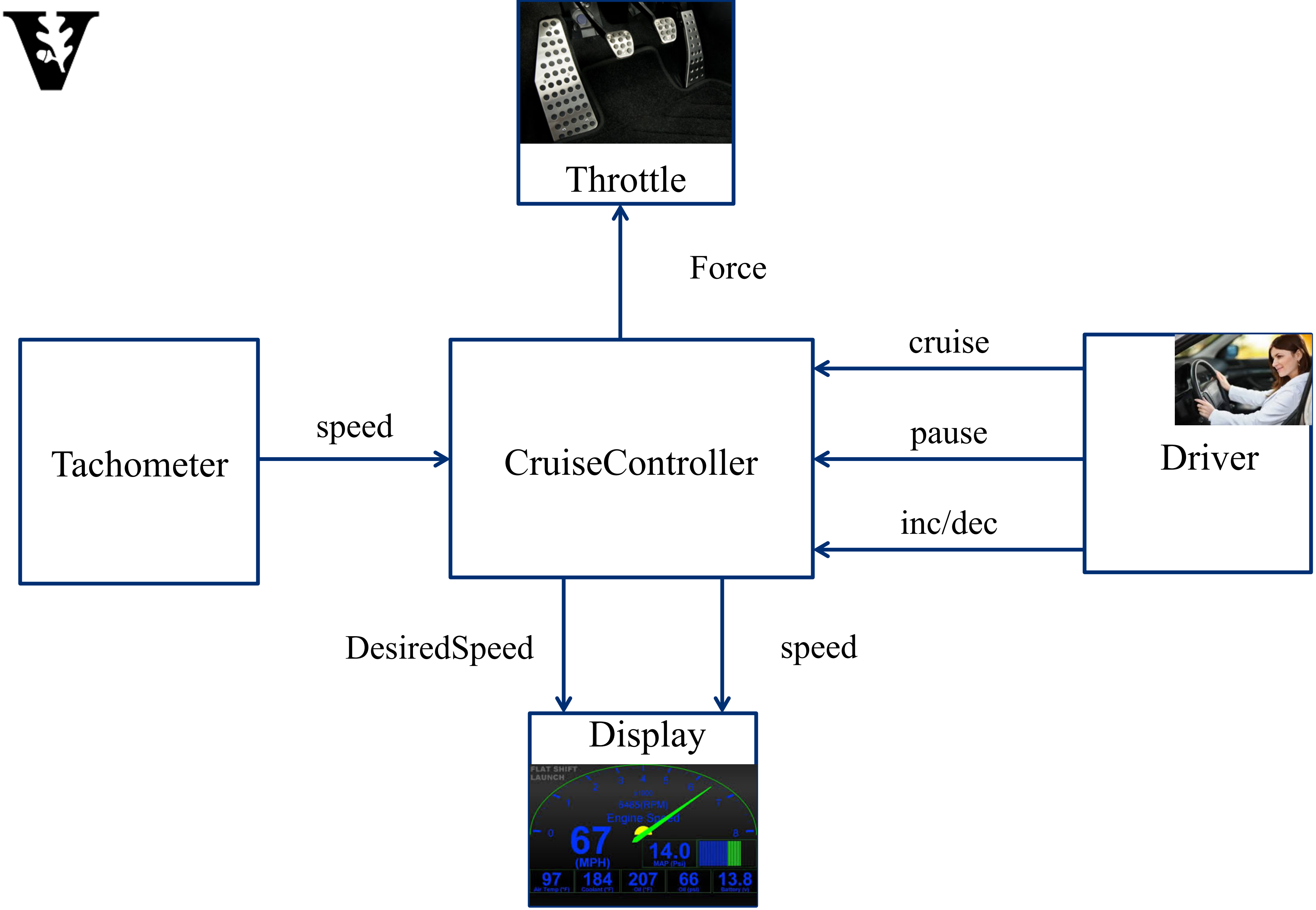
And who supplies it?

Interfaces for Components: Inputs and Outputs



What should be the outputs of the CruiseController?

And who needs these outputs?



Throttle

Force

Tachometer

speed

CruiseController

cruise

pause

inc/dec

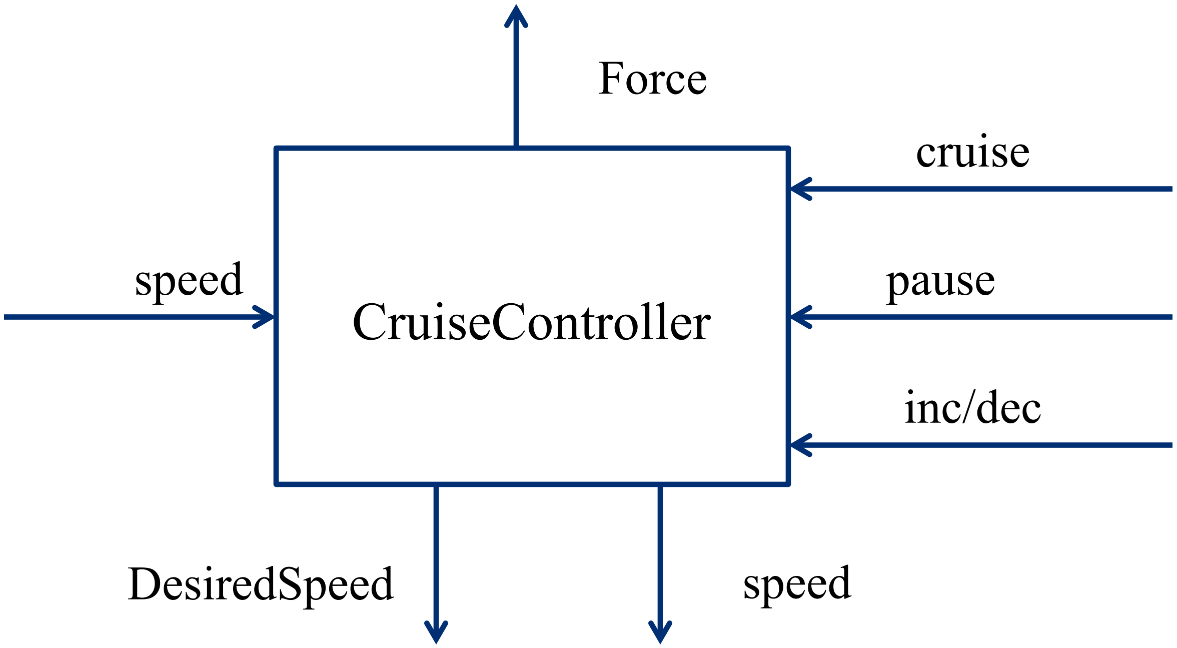
Driver

DesiredSpeed

speed

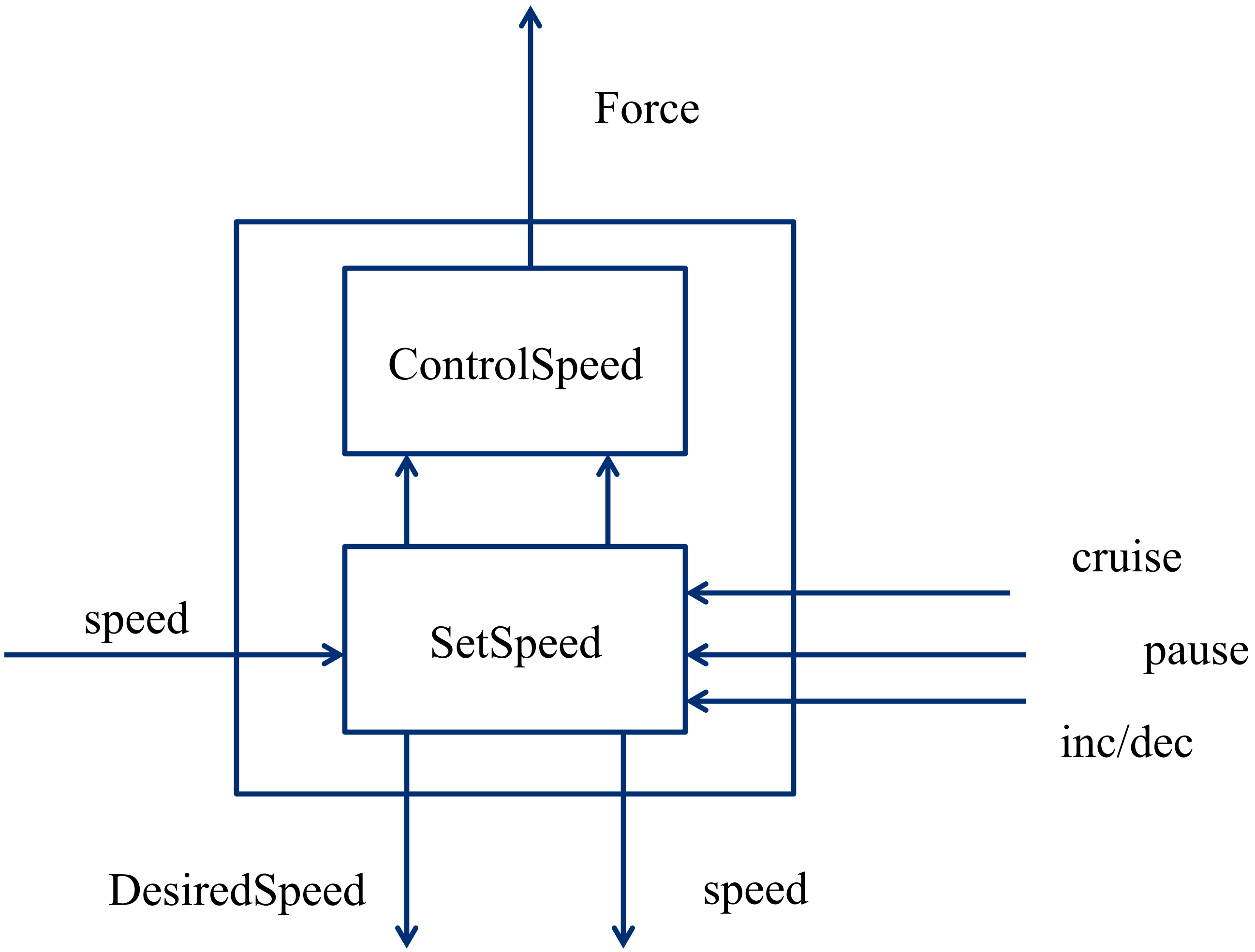
Display

Compositional Design

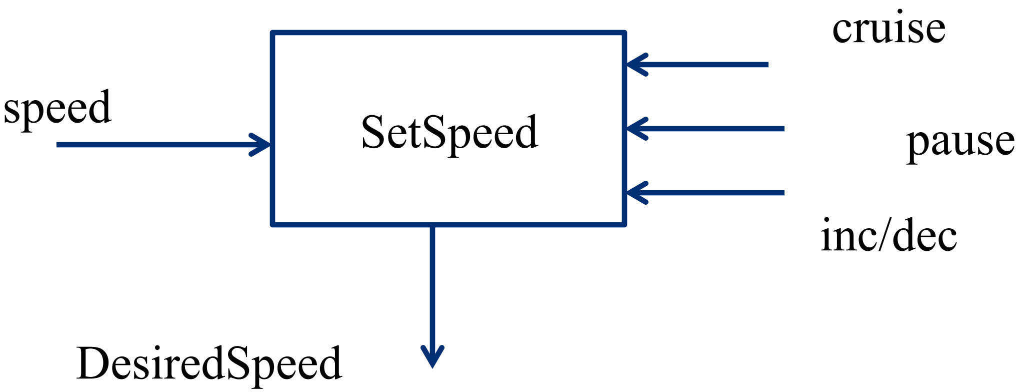


How to break up the computation of the cruise controller into subtasks?

Decomposing the Cruise Controller

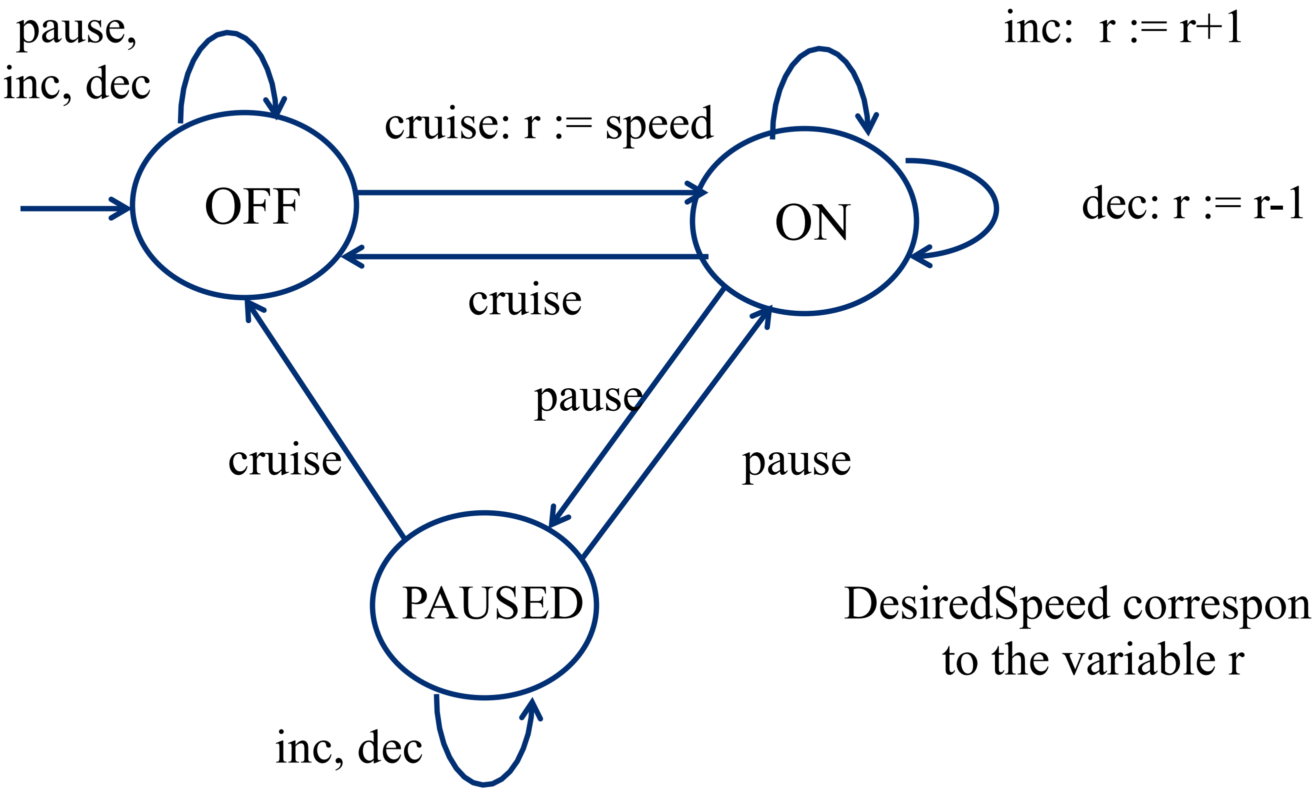


Designing SetSpeed Component



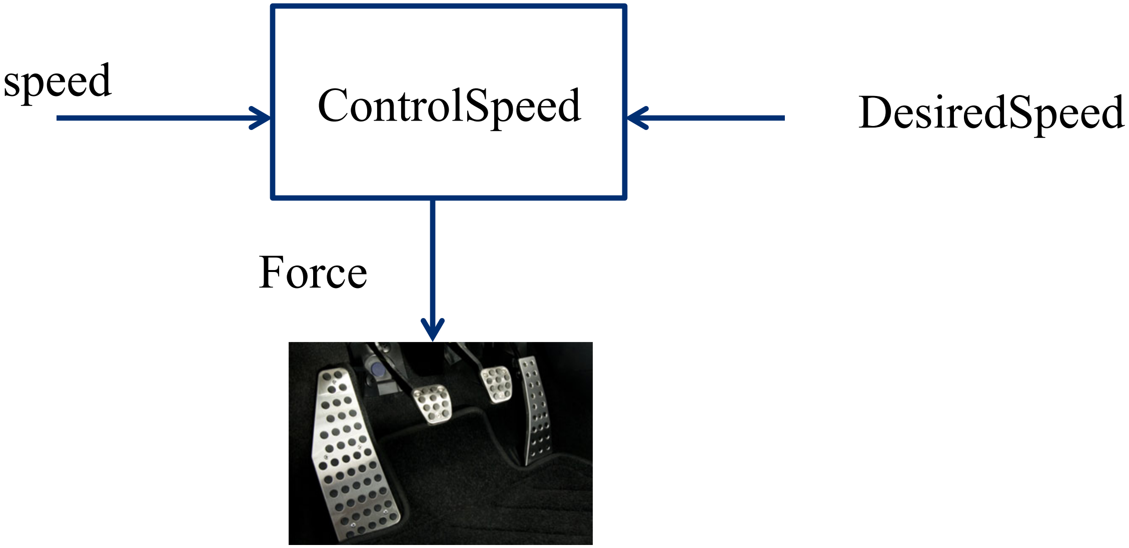
Goal: Compute the desired cruising speed in response to the commands from the driver

Designing SetSpeed: State Machines



DesiredSpeed corresponds
to the variable r

Designing ControlSpeed Component



speed

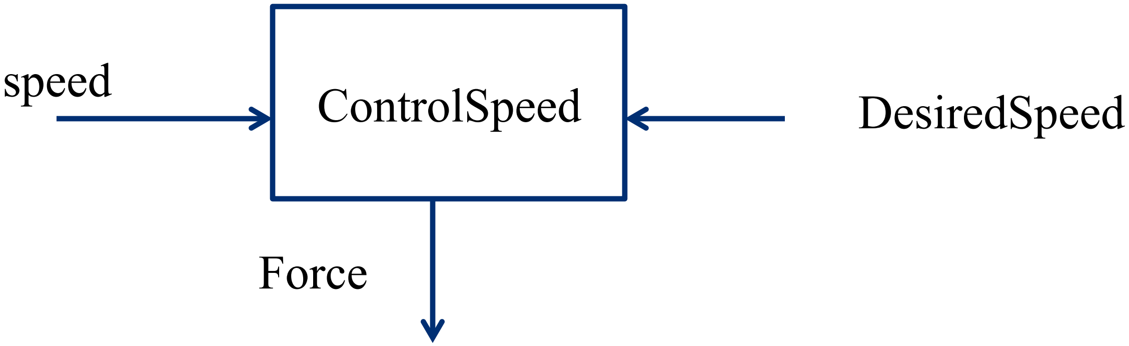
ControlSpeed

DesiredSpeed

Force

Goal: Determine the force to be applied to throttle so that speed becomes equal to DesiredSpeed

Capturing Requirements



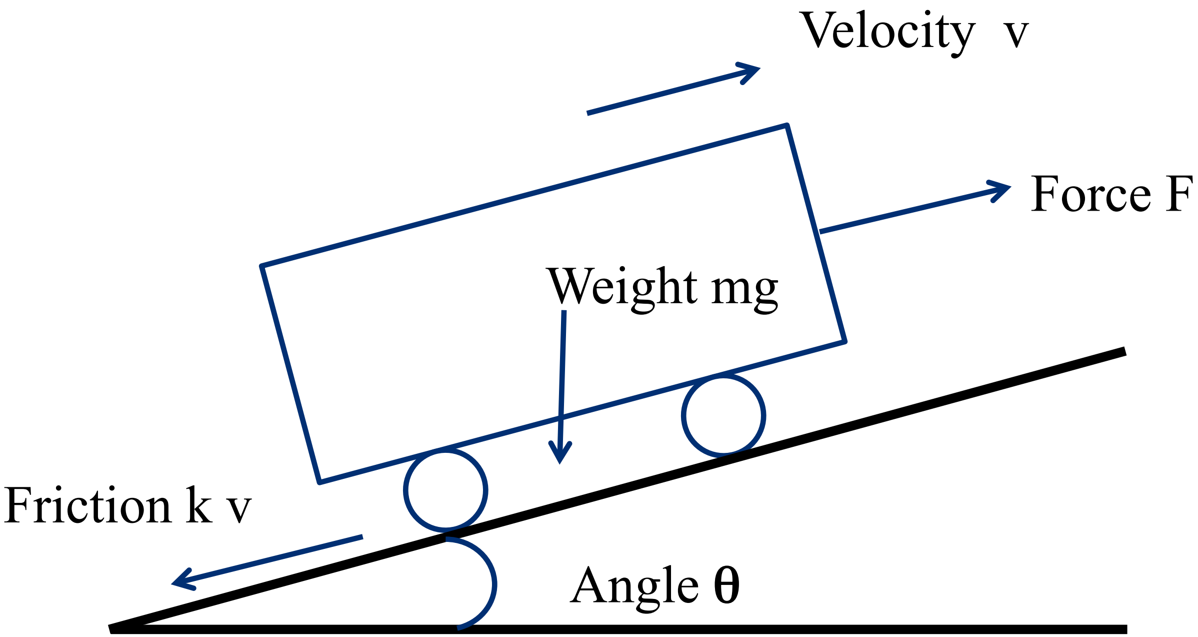
Requirements: Mathematically precise description of what a system is supposed to do.

Writing requirements is key to ensuring reliability of systems

Requirement 1: Actual speed eventually converges to desired speed

Requirement 2: Speed of the car stays “stable”

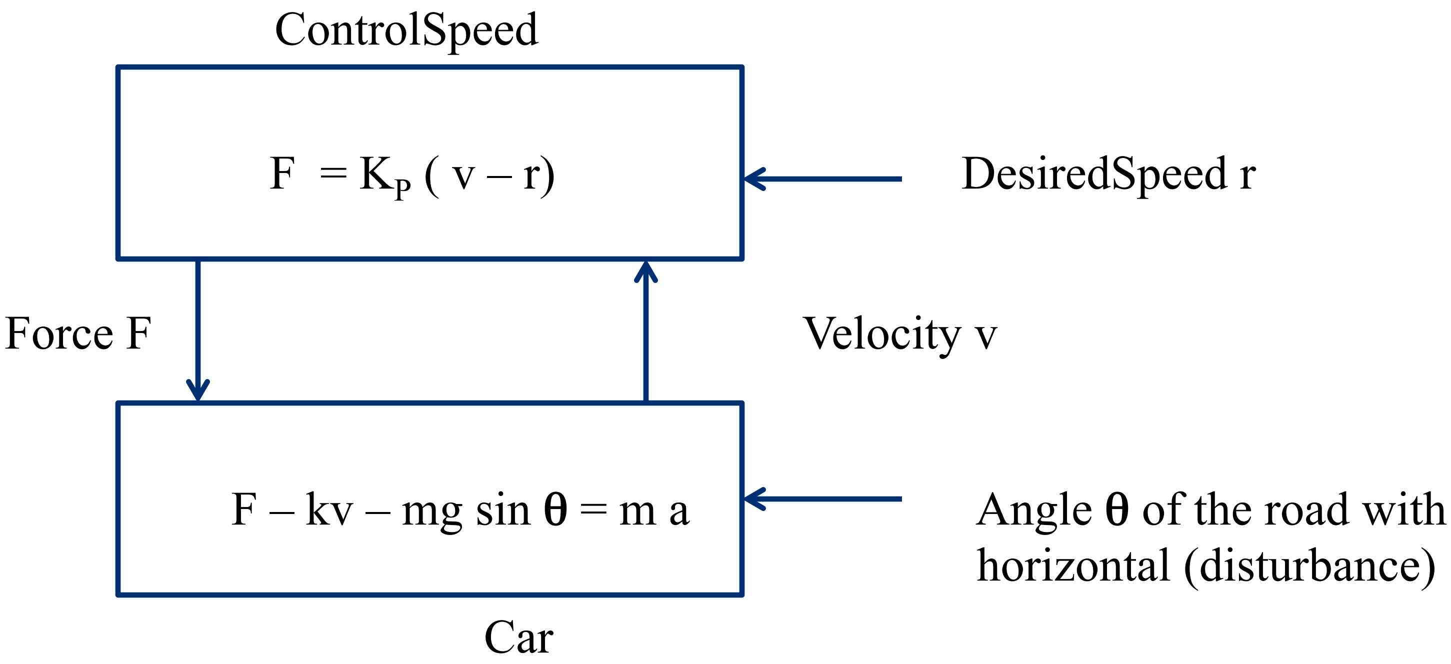
A bit of Physics: Modeling a car



Newton's law of motion gives

$$F - kv - mg \sin \theta = m\, a$$

ControlSpeed Component



ControlSpeed

$F \; = K_p \, (v - r)$

DesiredSpeed r

Force F

Velocity v

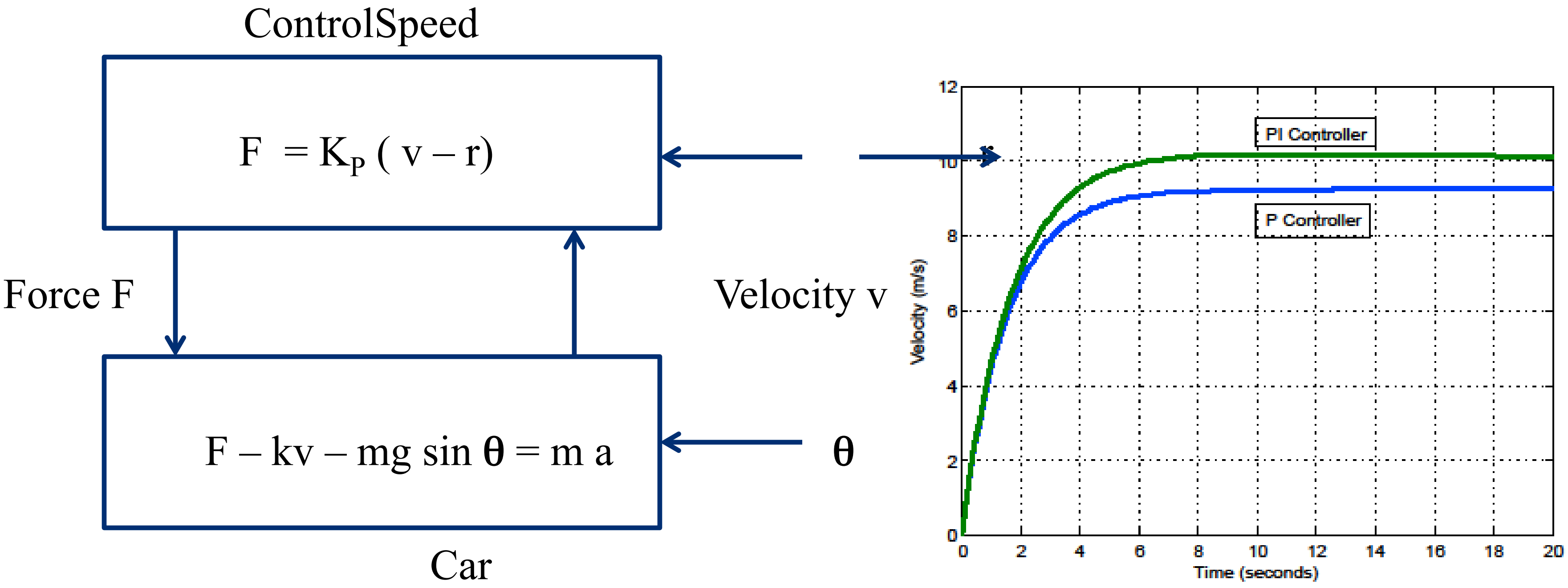
$F - kv - mg \sin \theta = m \, a$

Angle θ of the road with horizontal (disturbance)

Car

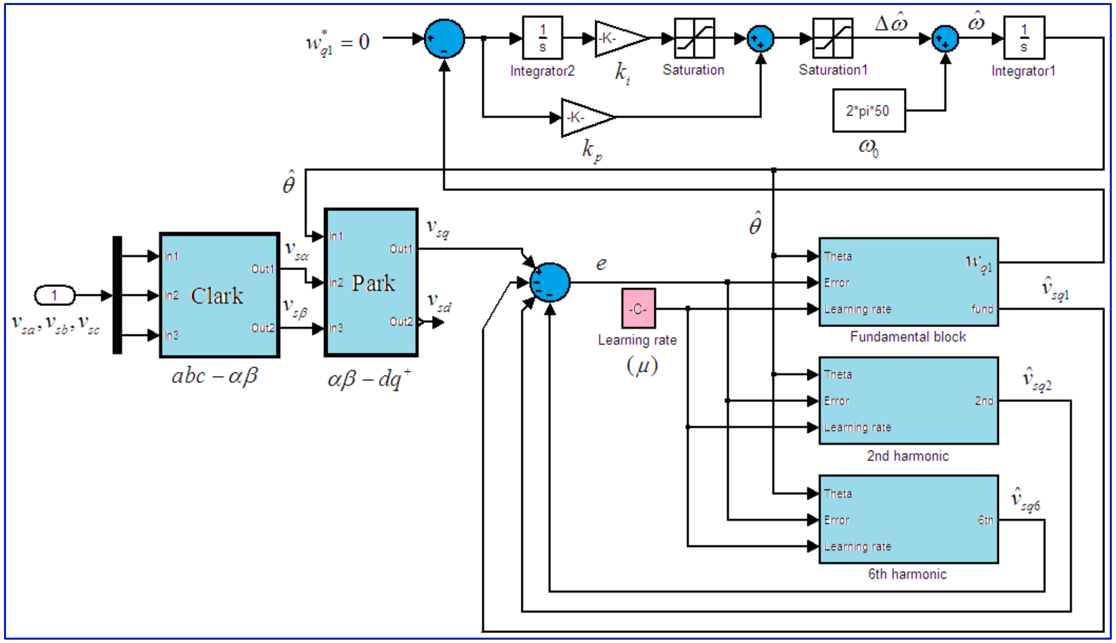
Control Theory: Mathematical techniques to compute force (F) as a function of velocity (v) and desired speed (r)

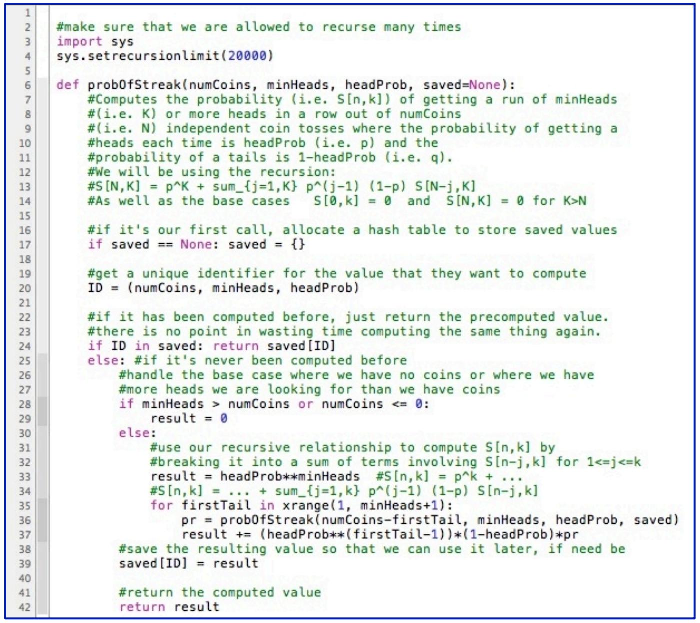
Does our controller work ?



Verification Tools: Allow you to check if system model indeed works as expected, that is, satisfies requirements

Model-based design



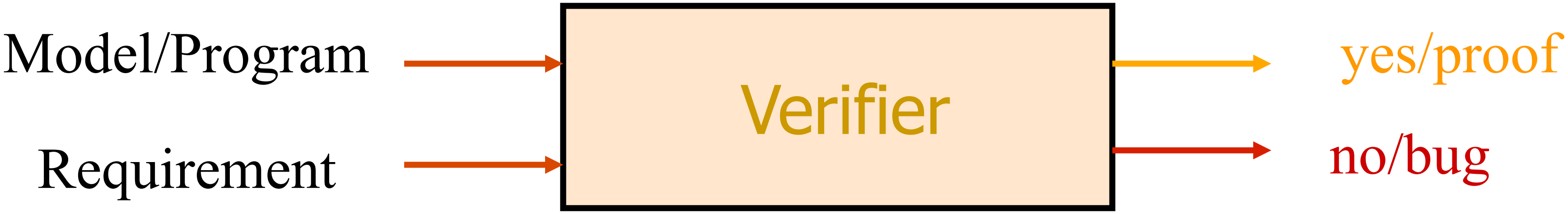


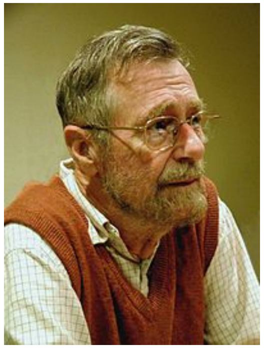
```python

#make sure that we are allowed to recurse many times
import sys
sys.setrecursionlimit(20000)

def probOfStreak(numCoins, minHeads, headProb, saved=None):
    #Computes the probability (i.e. S[n,k]) of getting a run of minHeads
    #(i.e. K) or more heads in a row out of numCoins
    #(i.e. N) independent coin tosses where the probability of getting a
    #heads each time is headProb (i.e. p) and the
    #probability of a tails is 1-headProb (i.e. q).
    #We will be using the recursion:
    #S[N,K] = p^K + sum_{j=1,K} p^(j-1) (1-p) S[N-j,K]
    #As well as the base cases   S[0,k] = 0  and  S[N,K] = 0 for K>N

    #if it's our first call, allocate a hash table to store saved values
    if saved == None: saved = {}

    #get a unique identifier for the value that they want to compute
    ID = (numCoins, minHeads, headProb)

    #if it has been computed before, just return the precomputed value.
    #there is no point in wasting time computing the same thing again.
    if ID in saved: return saved[ID]
    else: #if it's never been computed before
        #handle the base case where we have no coins or where we have
        #more heads we are looking for than we have coins
        if minHeads > numCoins or numCoins <= 0:
            result = 0
        else:
            #use our recursive relationship to compute S[n,k] by
            #breaking it into a sum of terms involving S[n-j,k] for 1<=j<=k
            result = headProb**minHeads  #S[n,k] = p^k + ...
            #S[n,k] = ... + sum_{j=1,k} p^(j-1) (1-p) S[n-j,k]
            for firstTail in xrange(1, minHeads+1):
                pr = probOfStreak(numCoins-firstTail, minHeads, headProb, saved)
                result += (headProb**(firstTail-1))*(1-headProb)*pr
        #save the resulting value so that we can use it later, if need be
        saved[ID] = result

        #return the computed value
        return result
```

Design using high-level block diagrams and state machines gets automatically compiled into low-level code !

Models not only of system being designed, but also of its environment

Simulation, Testing, and Verification





Program testing can be used to show the presence of bugs, but never their absence!

Edsger W. Dijkstra