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# The Compute Continuum: An Efficient Use of Edge-to-Cloud Computing Resources

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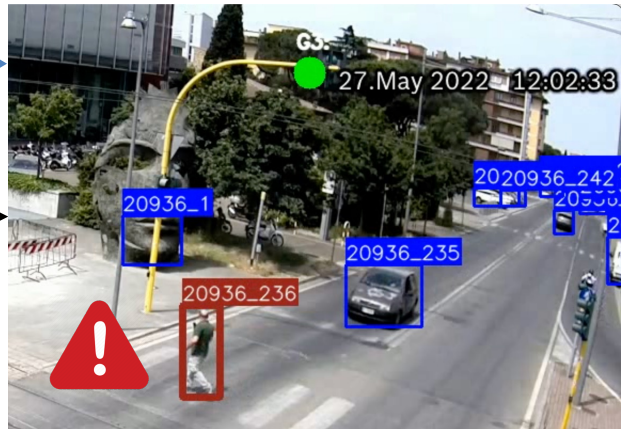
**Ada-Europe, Barcelona, 2024**

# From Data to (Real-time) Knowledge


Data

Knowledge

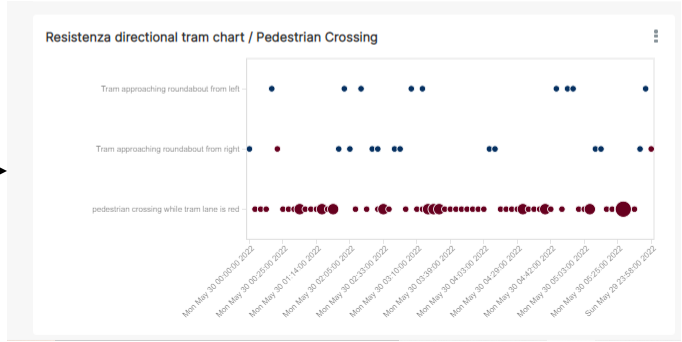



Object Detection & tracking

Semantic Extraction

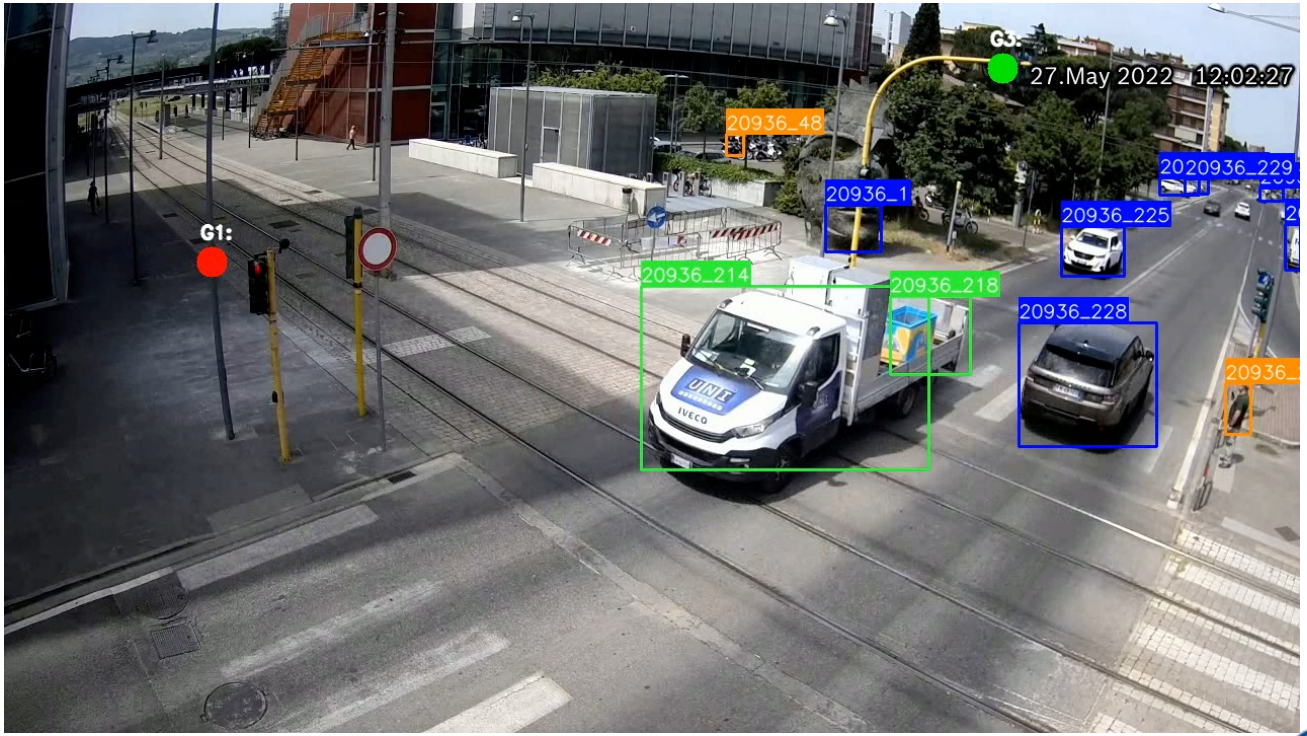
Hazard Detection: **PersonAtCrossWalk-SemaphoreRed**

*Guaranteed End-to-end response time*

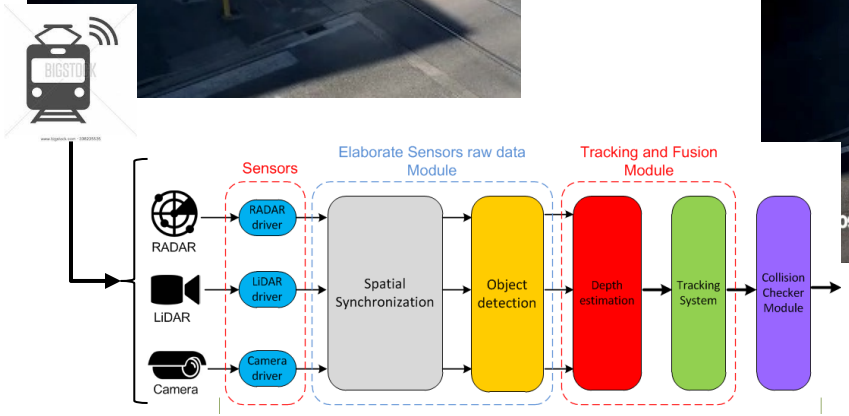



**Data-Analytics Workflow** executed by city resources

# From Data to (Real-time) Knowledge



# From Data to (Real-time) Knowledge


**Data-Analytics Workflow** executed by the tramway

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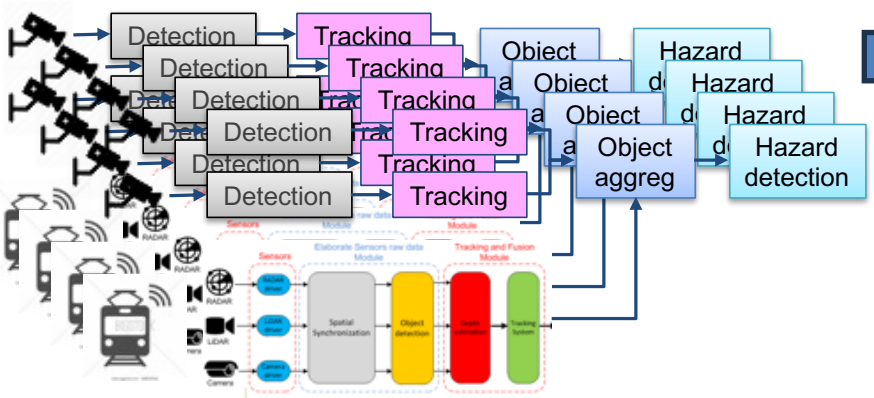
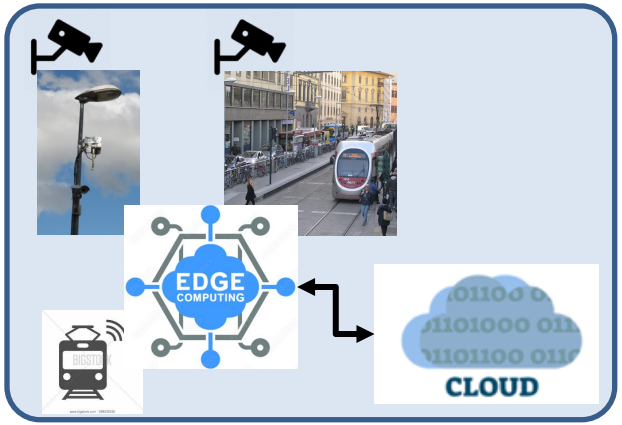
# Edge and Cloud Computing


Sensing capabilities of vehicles and cities can be effectively combined to identify hazardous situations




**Deploy and execute**

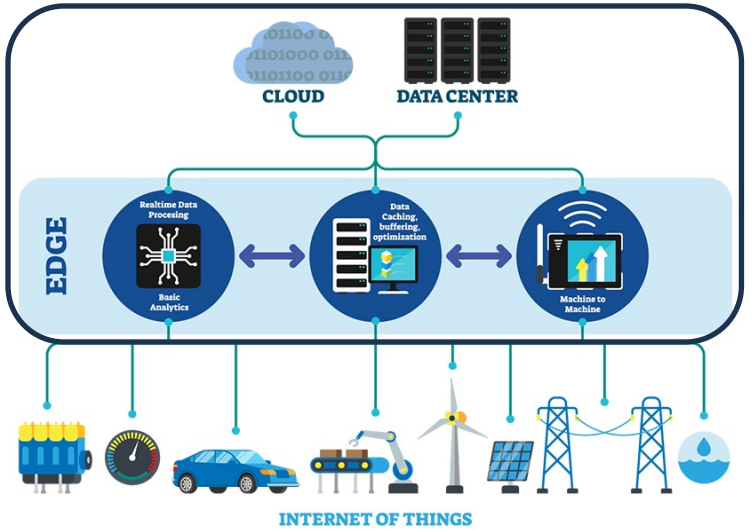



**Computing/Communication Resources**

# Compute Continuum: From Edge to Cloud

Abstracts the edge/cloud complexity

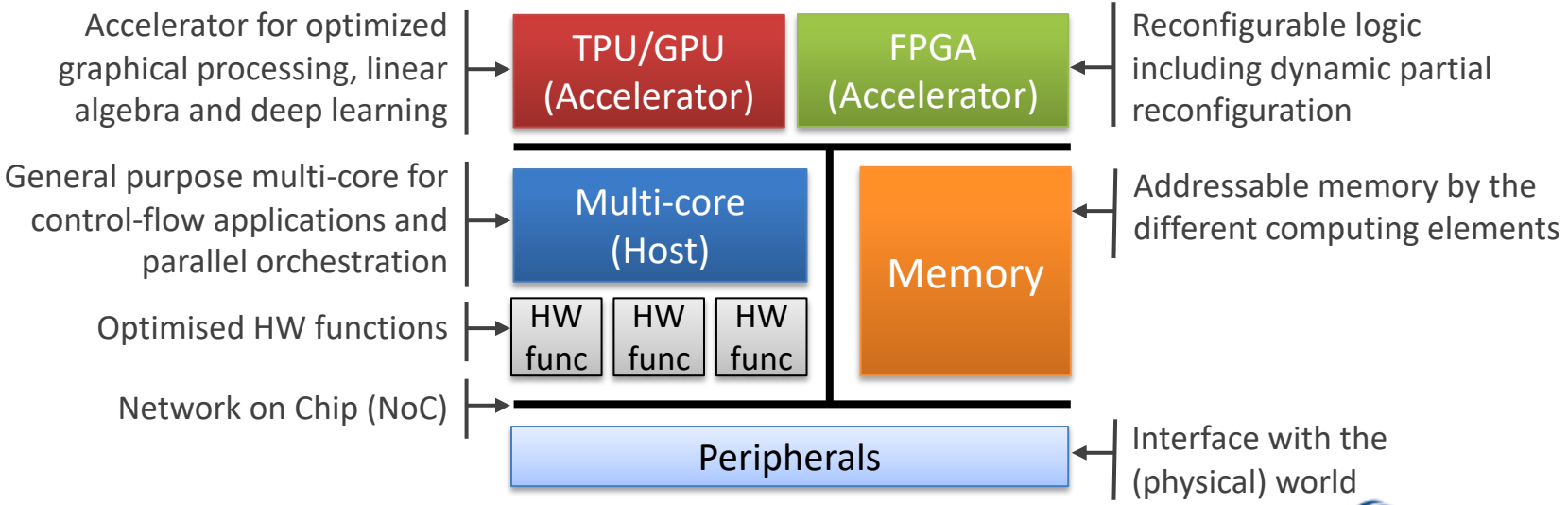
- Edge computing allows moving analytics close to data-sources
  - Enables faster **real-time processing**, higher privacy control and lower network costs
  - The use of powerful **heterogeneous and parallel embedded processor architectures** becomes fundamental
- Cloud computing provides computational intensive, batch processes and storage



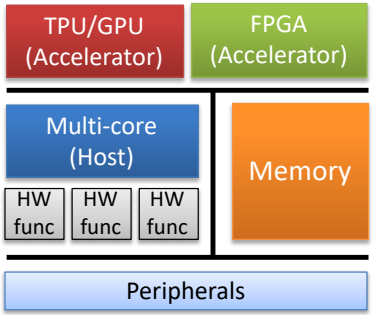

How are the data-analytics workflows **developed, deployed and efficiently executed** on highly heterogeneous **computing/communication resources?**

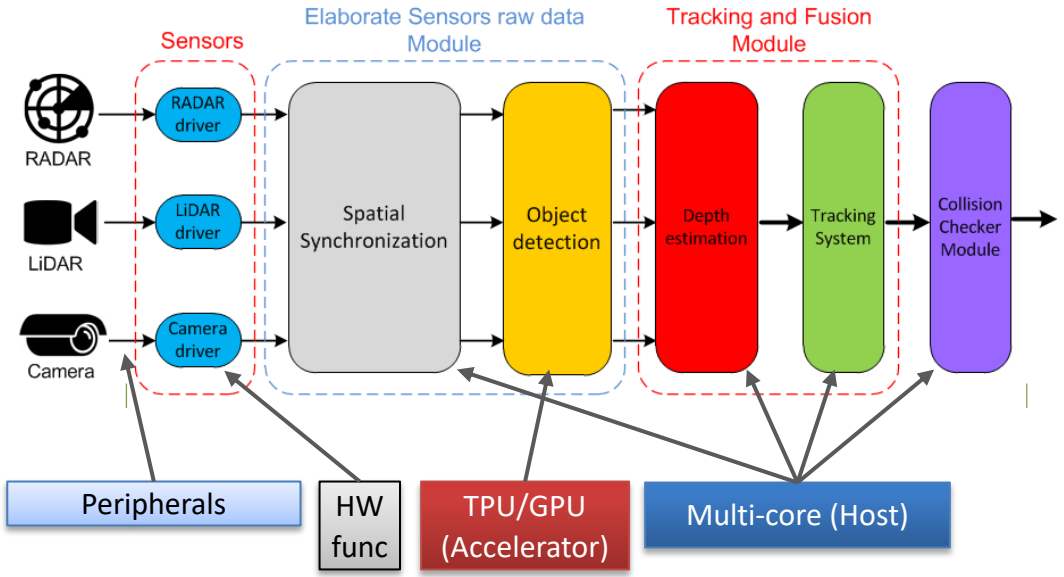
# Edge Computing

**Host-centric paradigm:** The parallel computation is orchestrated by the general-purpose multi-core



# Deploying on Edge Computing



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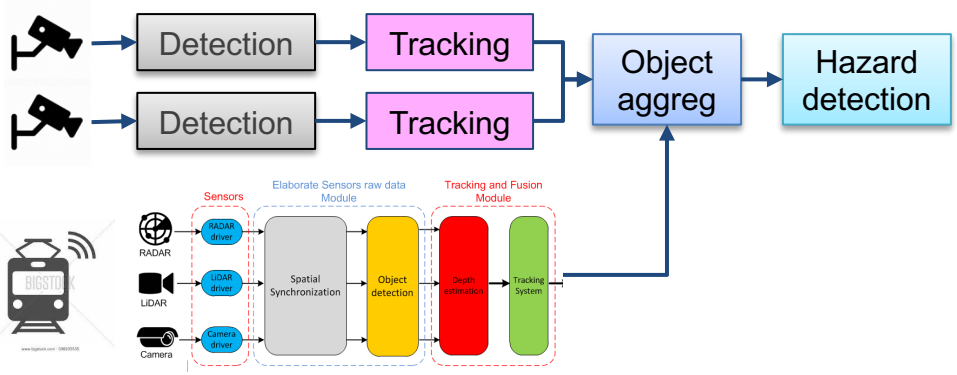
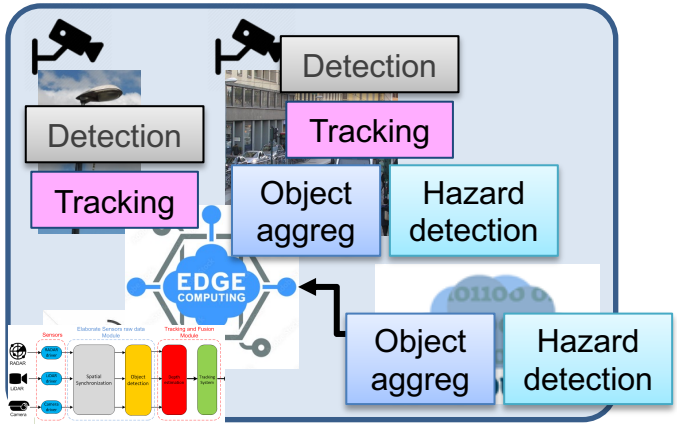
# Deploying on Cloud Computing


**Computing/Communication Resources**




kubernetes MINIO S3 docker Skupper LITHOPS



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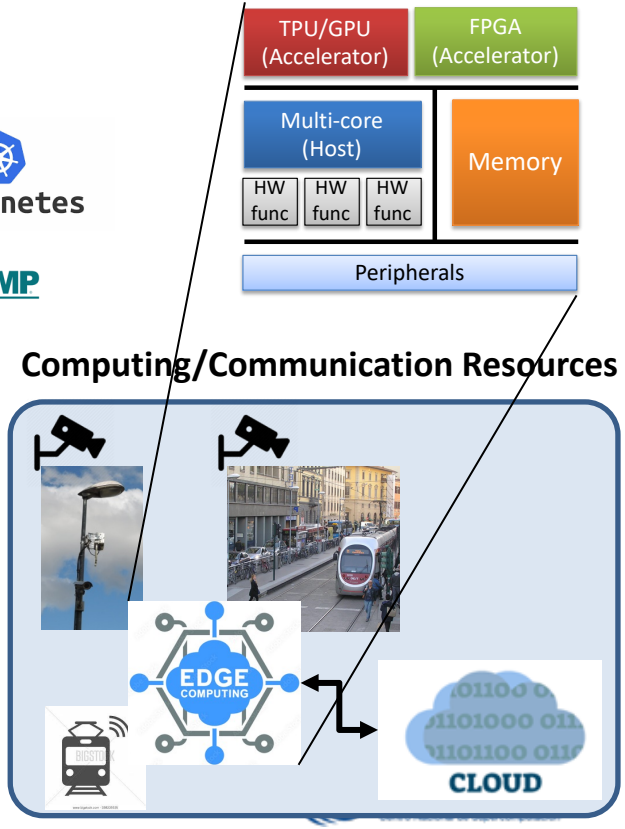
# Non-functional Requirements (NFR)

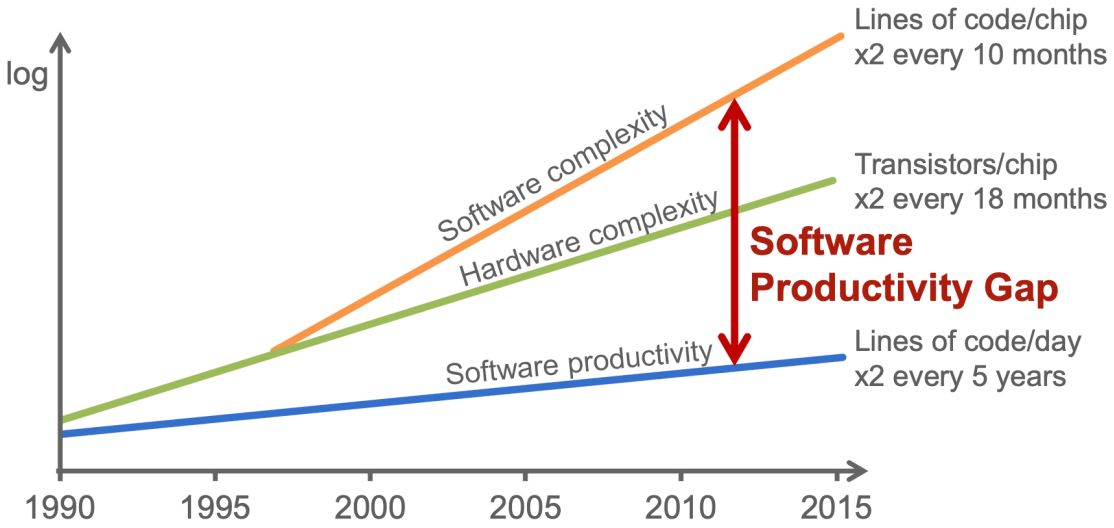
- Inherited due to the cyber-physical interactions, e.g.,
  - **Real-time:** The end-to-end response time (from sensor to actuator) must be within a given time budget
  - **Power/Thermal:** The energy/temperature of the computing elements must be within a given budget due to power supply/operational environment limitations
  - **Safety:** Built guaranteeing the correctness and integrity of its operation
  - **Security:** Prevent external elements not to affect the correctness and integrity of the system

# How to develop workflows on the compute continuum?

1. **Exploit the parallel performance capabilities** of the (different) processor architectures
2. **Efficiently distribute** the data-analytics workflow across the compute continuum
3. **Guarantee** functional correctness and the non-functional requirements

# SW Development Complexity




Source: ITRS & Hardware-dependent Software, Ecker et al., Springer

**Task-based Parallel Programming Models**

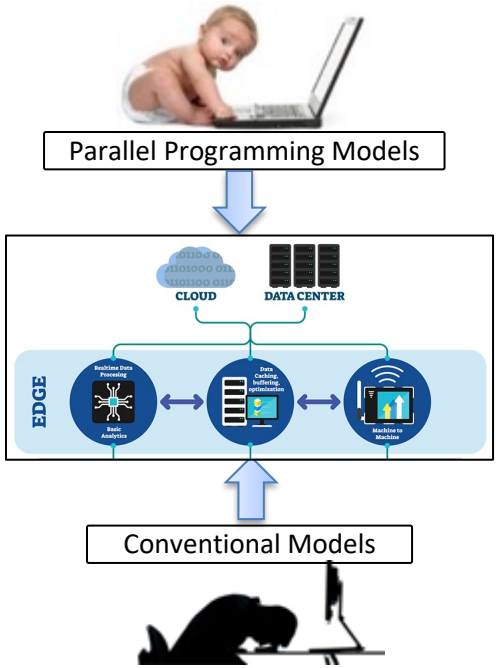
# Parallel Programming Models

- A set of programming elements to **describe** the parallel behaviour of an application and **abstract** the complexities of the underlying parallel platform
  - **Granularity level of parallelism** exploited: instruction, statement, loop, procedural
  - **Synchronization** model: coarse-grain, fine-grain
  - **Execution model**: fork-join, thread-pool, etc.
  - **Memory model**: Shared, distributed
- Commonly built on top of a base programming language

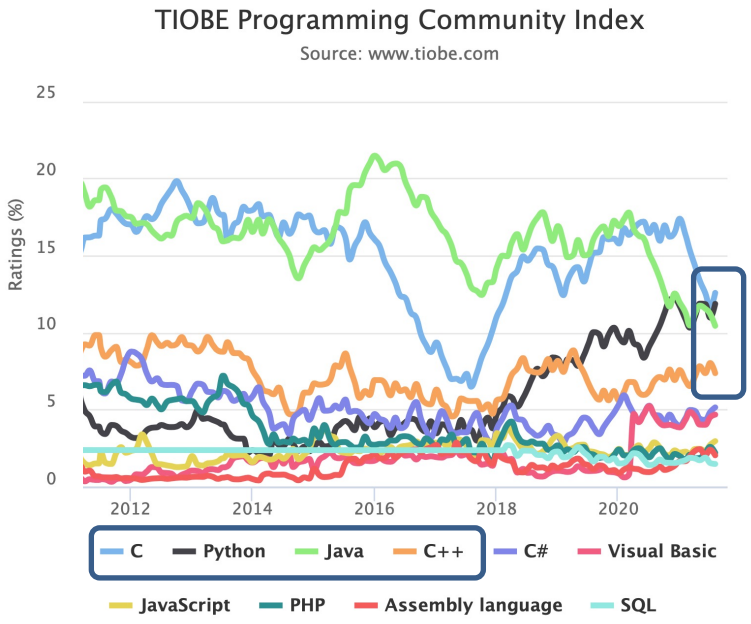
# Parallel Programming Models

Mandatory to enhance **productivity**

- **Programmability.** Abstracts the parallelism while hiding the underlying computing platform complexities
- **Portability/scalability.** The same source code is valid in different parallel platforms
- **Performance.** Rely on run-time mechanisms to exploit the performance capabilities of parallel platforms



# Parallel Programming Models and Programming Languages




| Model | Base Language | Type of PPM | Type of architect | Type of Parallelism |
|---|---|---|---|---|
| **CUDA** | C/C++, Python | HW-centric | NVIDIA GPU | Struct/ Unstruct |
| **OpenCL** | C/C++ | App-centric | GPU/ FPGAs | Struct |
| **OpenMP** | C/C++ | Parallel-centric | Shared mem | Struct/ **Unstruct** |
| **Pthreads** | C/C++ | Parallel-centric | Shared mem | Unstruct |
| **MPI** | C/C++, Python | Parallel-centric | Distributed mem | Unstruct |
| **COMPSs** | C++, Java Python | Parallel-centric | Distributed mem | **Unstruct** |
| **Spark** | Java, Python | Parallel-centric | Distributed mem | Struct |
| **Ray** | C++,Java Python | Parallel-centric | Distributed mem | Unstruct |

# Why OpenMP?

**Mature language** constantly reviewed (last release Nov 2024, v6.0)

- Defacto industrial standard in HPC
- Active research community with an **increasing interest** on the edge domain

**Productivity** in parallel programming

- 
- Portability
  - Supported by many chip vendors
- Programmability
  - Interoperability with other models (CUDA, OpenCL)
  - Allows incremental parallelization

OpenMP

# Why COMPSs?

**Programming distribute framework** highly inspired in the OpenMP tasking model

- The code is annotated to describe task and data dependencies

**Productivity** in distributed programming

- Performance
- 
- Programmability
  - Interoperability with other programming models (OpenMP)
  - Allows incremental parallelization

**You can choose any other task-based parallel programming model you like!**

COMPSs

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# OpenMP Tasking Model

## Sequential version

```
void main() {
     int x,y;
     f1(&x,&y);
     f2(x);
     f3(y);
}
```

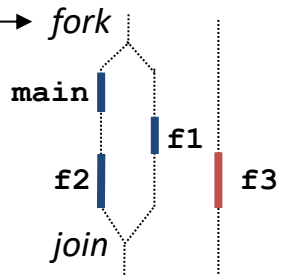
*Executes on the host*

*Executes on the accelerator*

## OpenMP version

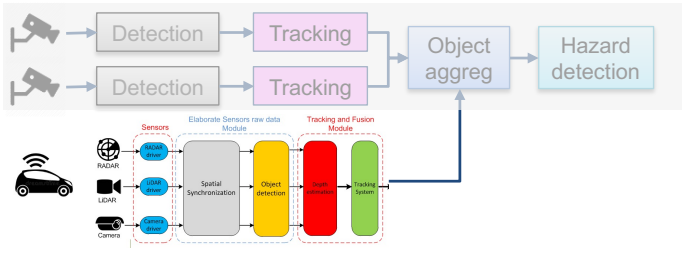
```
void main() {
     #pragma omp parallel
     #pragma omp single
     {
          int x,y;
          #pragma omp task depend(out:x,y)
          { f1(&x,&y); }
          #pragma omp task depend(in:x)
          { f2(x); }
          #pragma omp target map(to:y) depend(in:y)
          { f3(y); }
     }
}
```

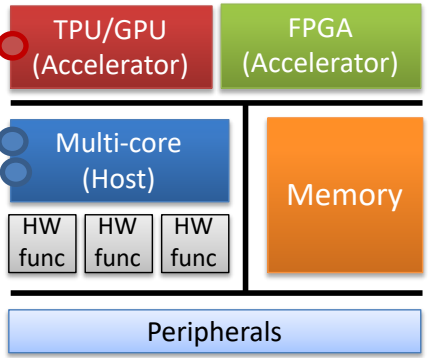
1. Open parallelism




2. Tasks executed on the host

3. Tasks executed on the host and accelerator when f1 completes

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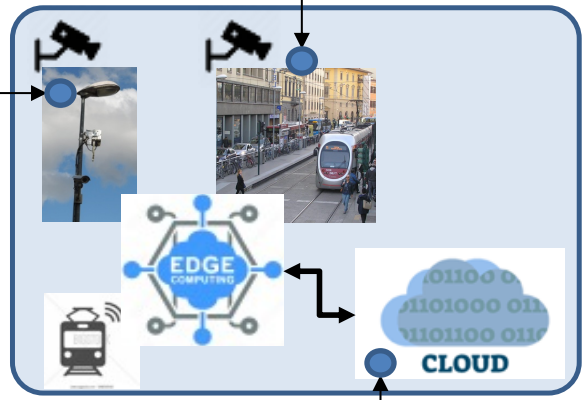
# COMPSs Tasking Model

## Sequential version

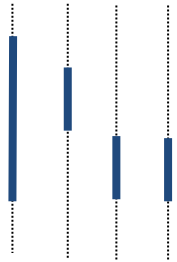
```
def f1():
    …
    return x,y
def f2(x):
    …
def f3(y)
    …
def main():
    x,y=f1()
    f2(x)
    f3(y)
```

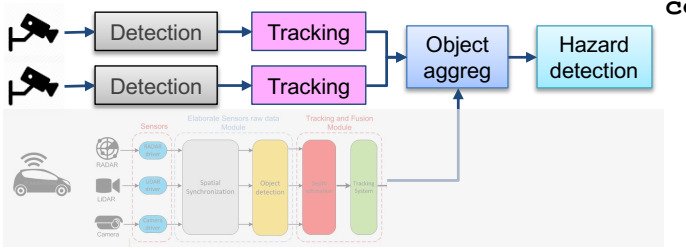
## COMPSs version

```
@task(x=OUT,y=OUT)
def f1():
    …
    return x,y
@task(x=IN)
def f2(x):
    …
@task(y=IN)
def f3(y)
    …
def main():
    x,y=f1()
    f2(x)
    f3(y)
    compss_wait()
```




Tasks executed across the compute continuum

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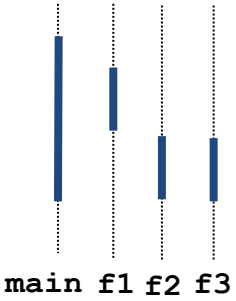
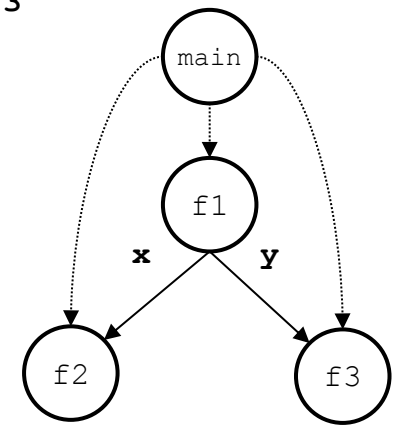
# Task Dependency Graph (TDG)

COMPSs version

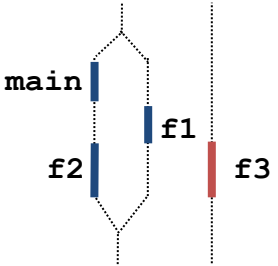
```
@task(x=OUT,y=OUT)
def f1():
    …
    return x,y
@task(x=IN)
def f2(x):
    …
@task(y=IN)
def f3(y)
    …
def main():
    x,y=f1()
    f2(x)
    f3(y)
```




OpenMP version

```
void main() {
    #pragma omp parallel
    #pragma omp master
    {
        int x,y;
        #pragma omp task depend(out:x,y)
        { f1(&x,&y); }
        #pragma omp task depend(in:x)
        { f2(x); }
        #pragma omp target map(to:y) depend(in:y)
        { f3(y); }
```

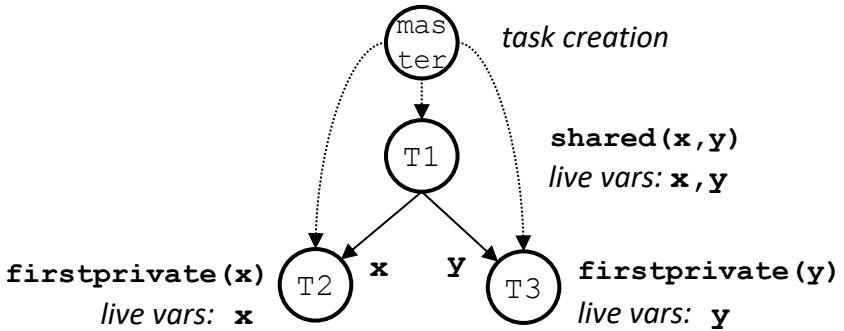


# Task Dependency Graph (TDG)

A representation of the parallel nature of a workflow

- Includes all the information for functional and non-funcional correctness
  - **Parallel units** and **synchronization** dependencies
  - **Liveness analysis of variables** and **data-sharings** involved in the parallel execution
- Independent from the targeted parallel platform (but can include HW dependent information)
  - **Execution characterisation** of parallel units (e.g., time, energy, memory behaviour)

```
#pragma omp parallel
#pragma omp master
{
    int x,y;
    #pragma omp task depend(out:x,y) shared(x,y) // T1
    { f1(&x,&y); }
    #pragma omp task depend(in:x) firstprivate(x) // T2
    { f2(x); }
    #pragma omp task depend(in:y) firstprivate(y) // T3
    { f3(y); }
}
```



# Principle behind Tasking Models

- Tasking provides a great expressiveness to describe the parallel nature of applications
  - It specifies **what** the application does and not **how** it is done
  - The framework is responsible of orchestrating the execution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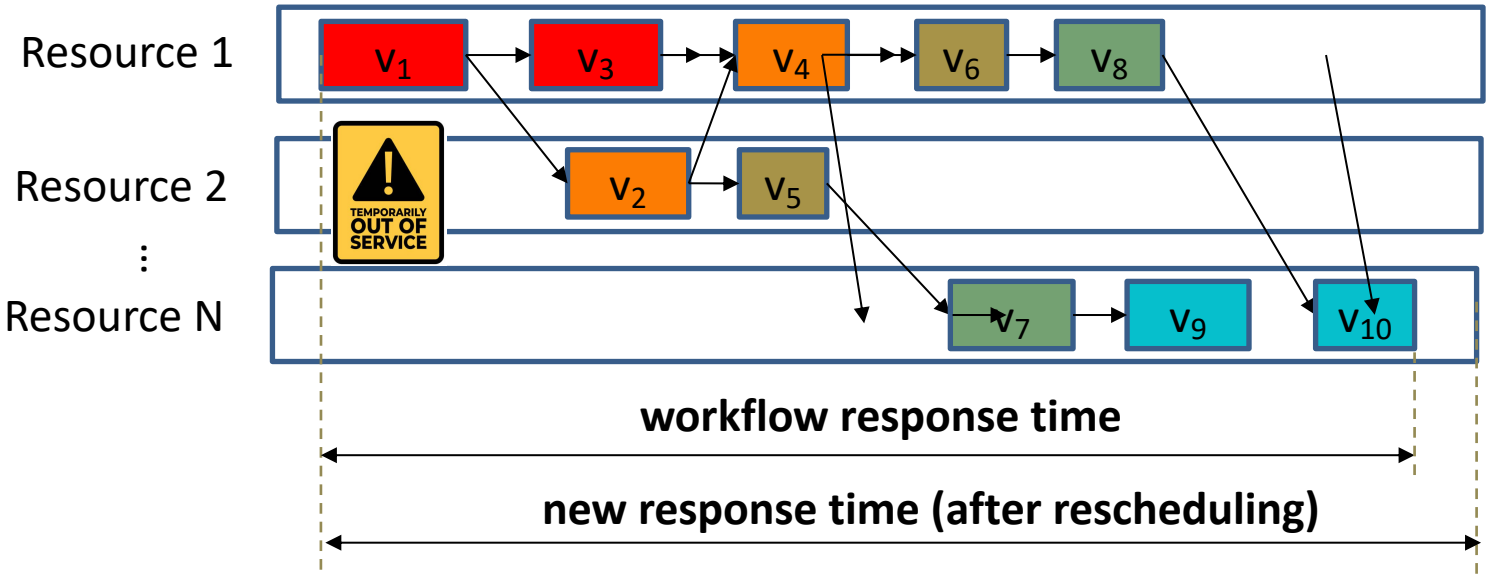
# Orchestration of resources



# Conclusions

1. The compute continuum provides the computing capabilities to cope with the performance requirements of complex data-analytics workflows, and…
2. … task-based parallel programming models allows to **reasoning about functional and time predictability** while removing from developers the responsibilty of managing the complexity of the compute continuum

**VERY INTERESTING RESEARCH IS STILL PENDING!**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