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EXTRACT
A distributed data-mining software platform for extreme data across the compute continuum

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

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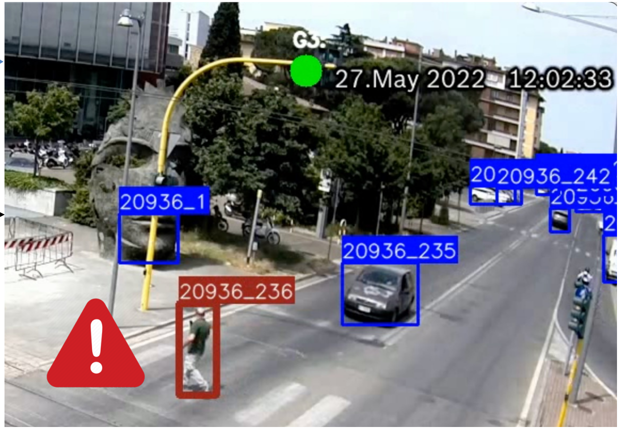
Ada-Europe, Barcelona, 2024

From Data to (Real-time) Knowledge

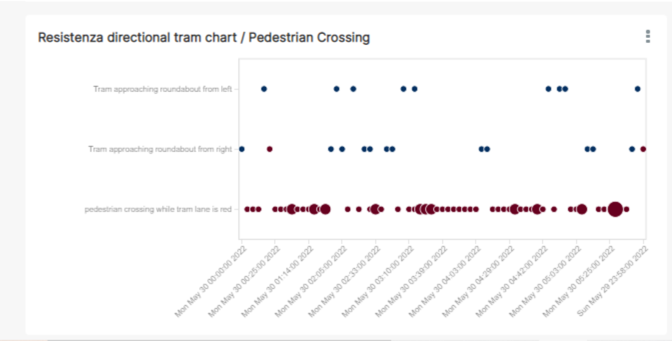
Data **Knowledge**



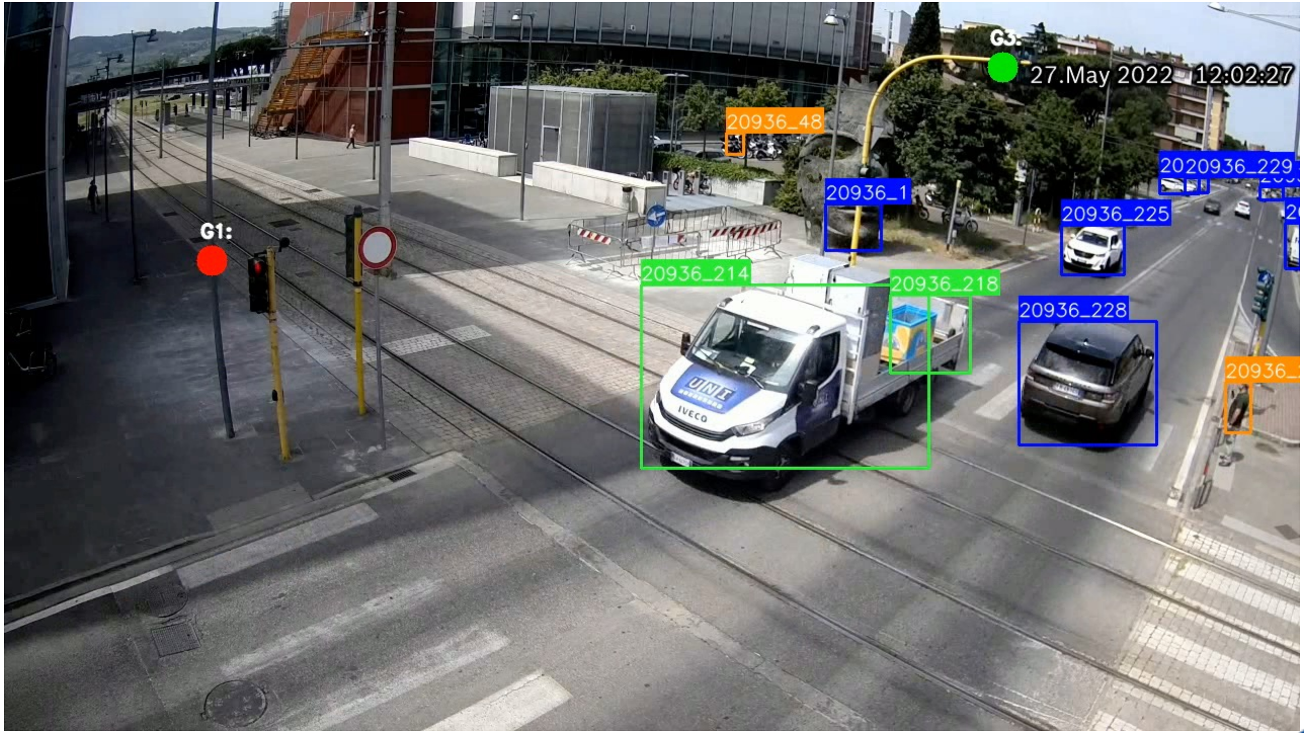
Object Detection & tracking → Semantic Extraction → **Hazard Detection: PersonAtCrossWalk-SemaphoreRed**

Guaranteed End-to-end response time

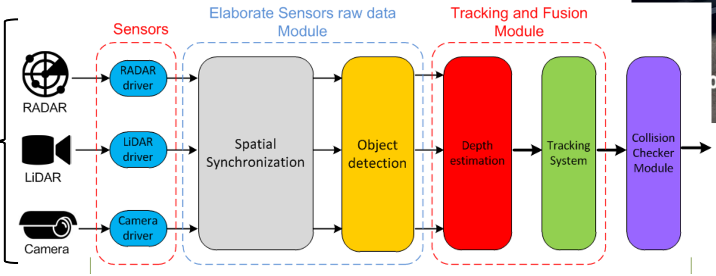
Data-Analytics Workflow executed by city resources

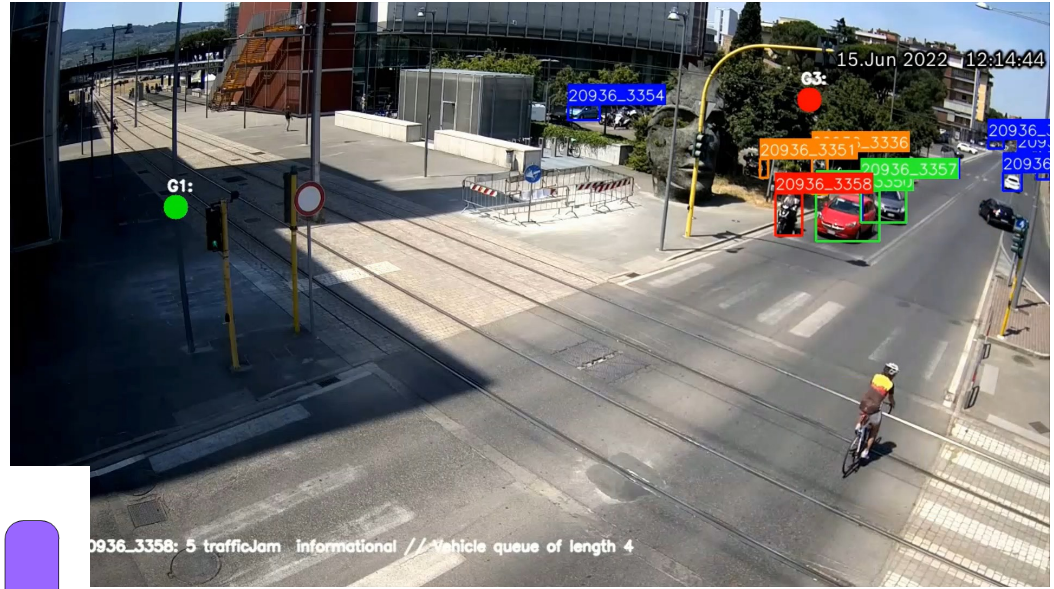


From Data to (Real-time) Knowledge



From Data to (Real-time) Knowledge





Data-Analytics Workflow executed by the tramway

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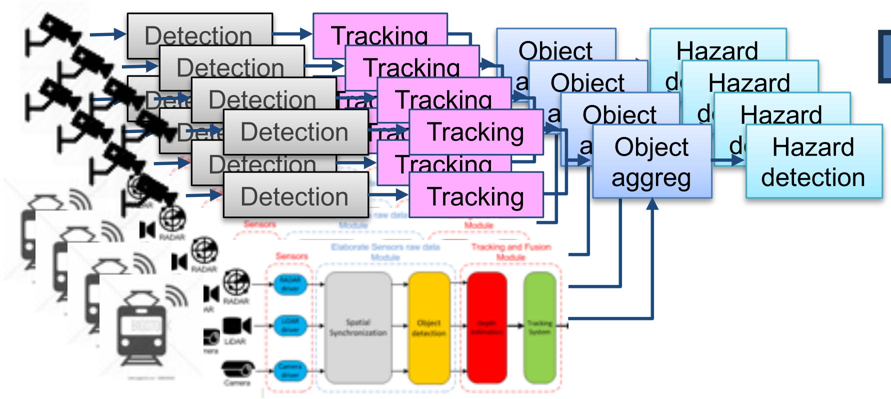
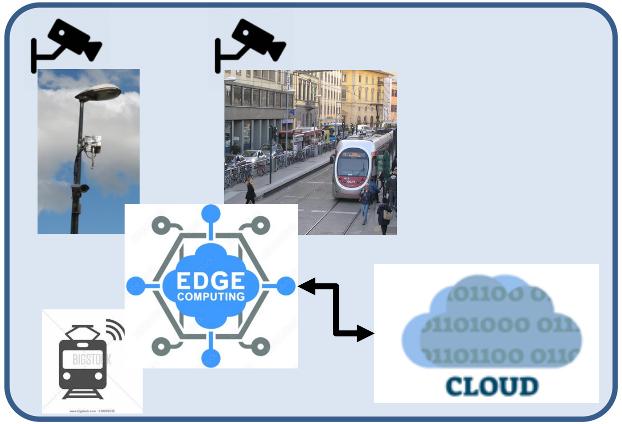
Edge and Cloud Computing

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



Deploy and execute

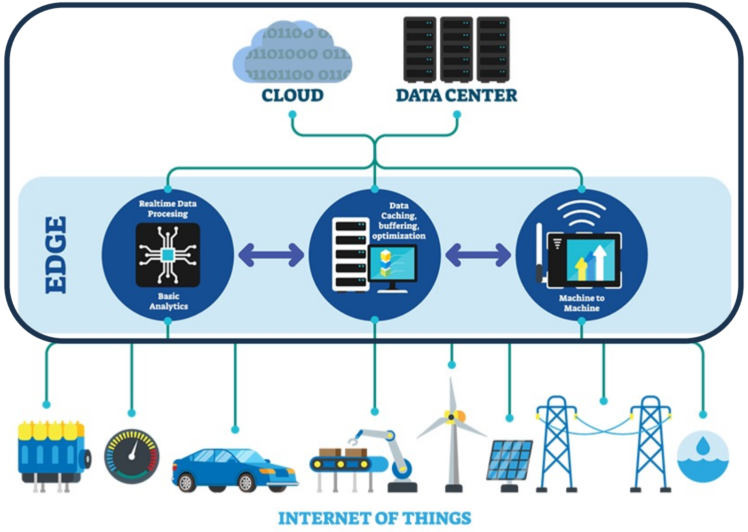


Computing/Communication Resources

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

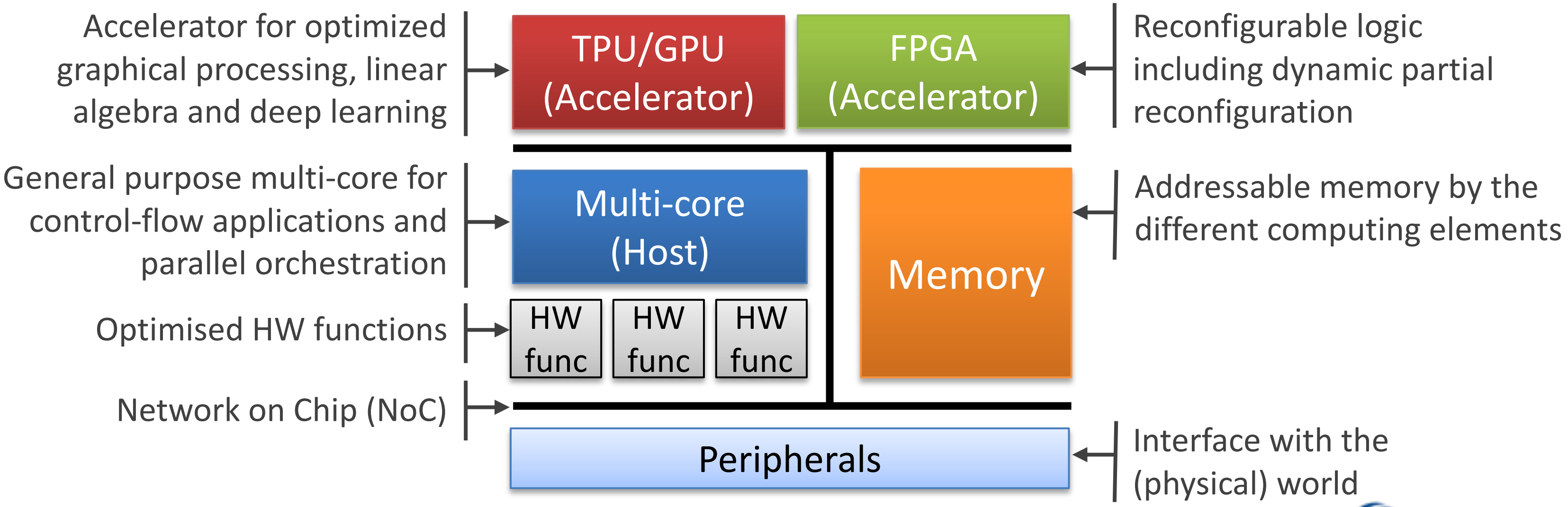


Compute Continuum

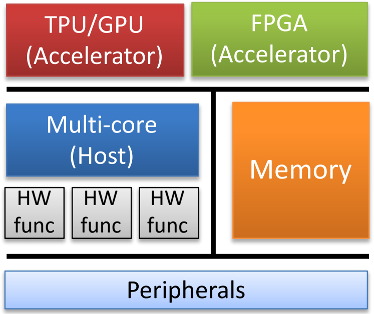
How are the data-analytics workflows <u>**developed, deployed and efficiently executed**</u> on highly heterogeneous **computing/communication resources?**

Edge Computing

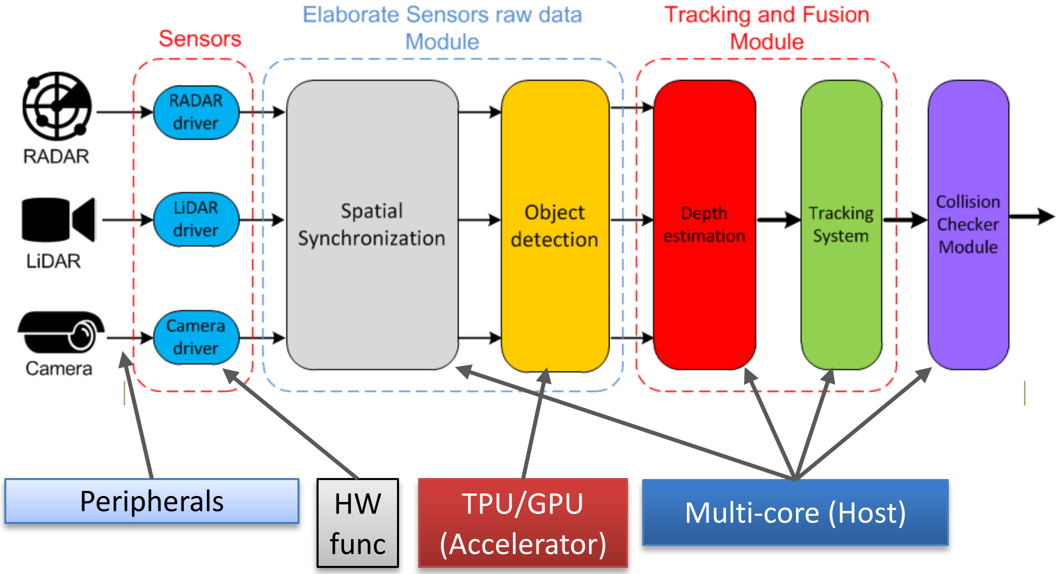
Host-centric paradigm: The parallel computation is orchestrated by the general-purpose multi-core



Deploying on Edge Computing



NVIDIA CUDA
RTEMS
AdaCore
POSIX pthreads
OpenMP



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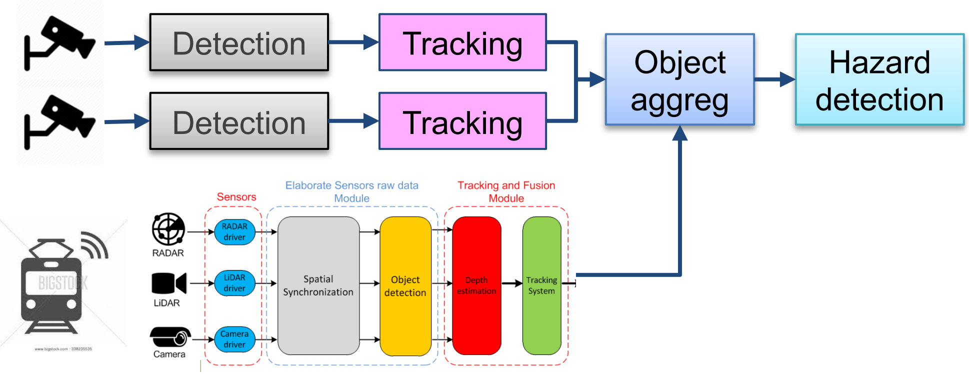
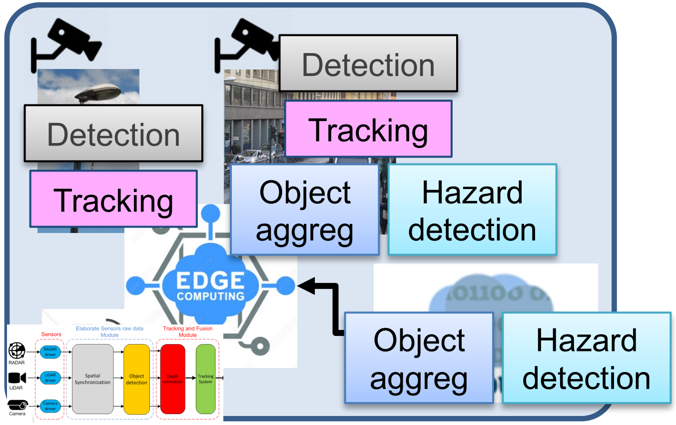
Deploying on Cloud Computing



Computing/Communication Resources



kubernetes S3 docker MINIO Skupper LITHOPS

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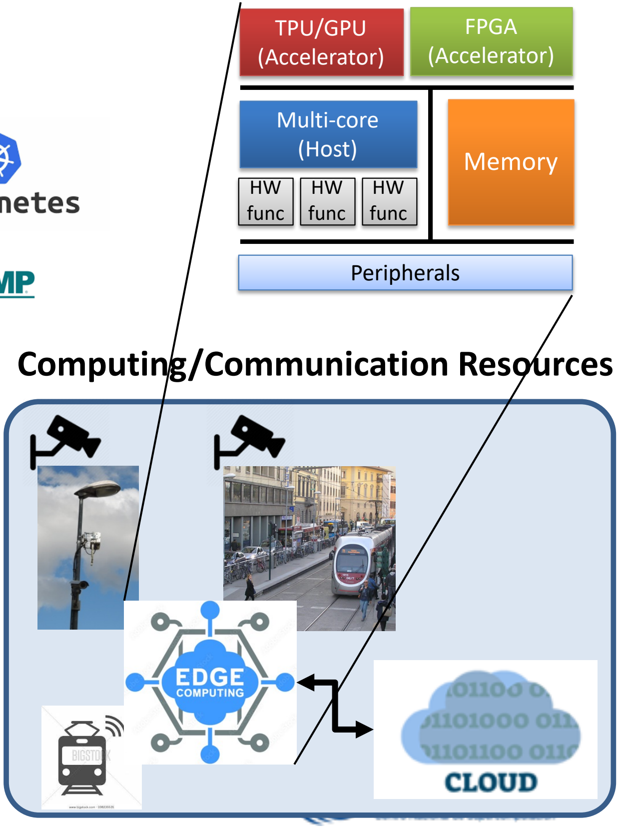
Non-functional Requirements (NFR)

- 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

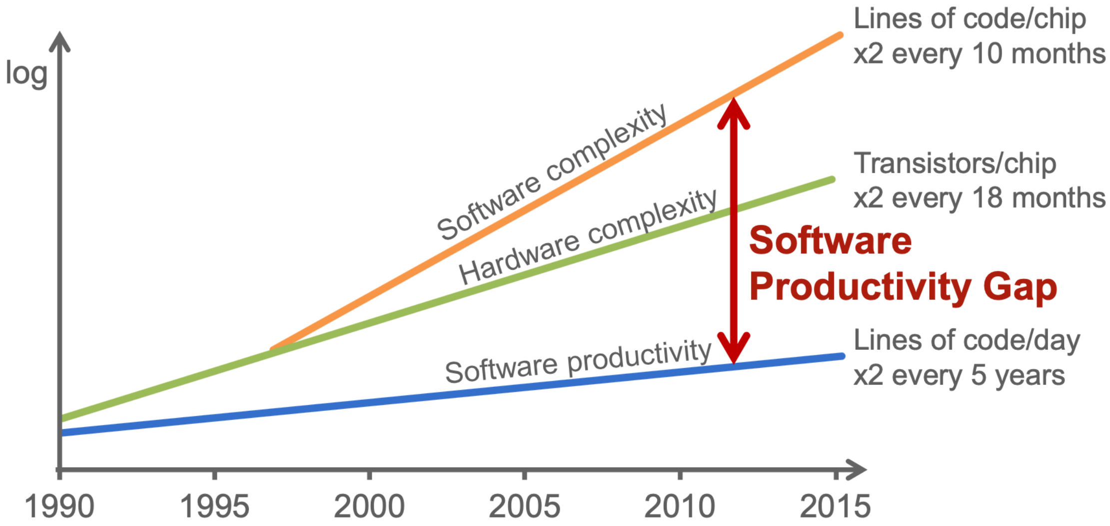
How to develop workflows on the compute continuum?

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

POSIX pthreads



SW Development Complexity



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

Task-based Parallel Programming Models

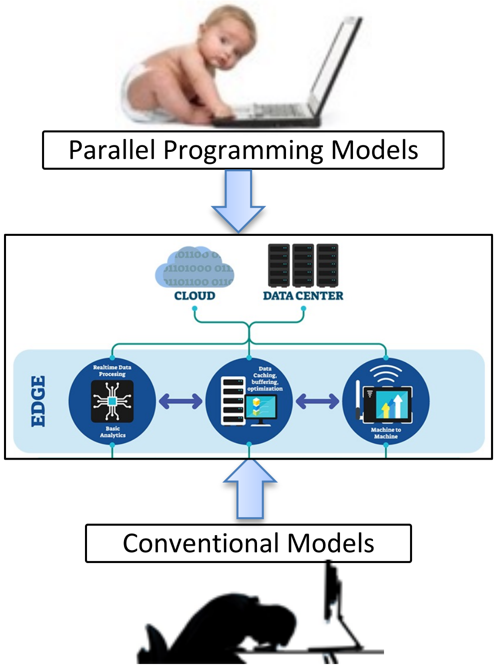
Parallel Programming Models

- 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

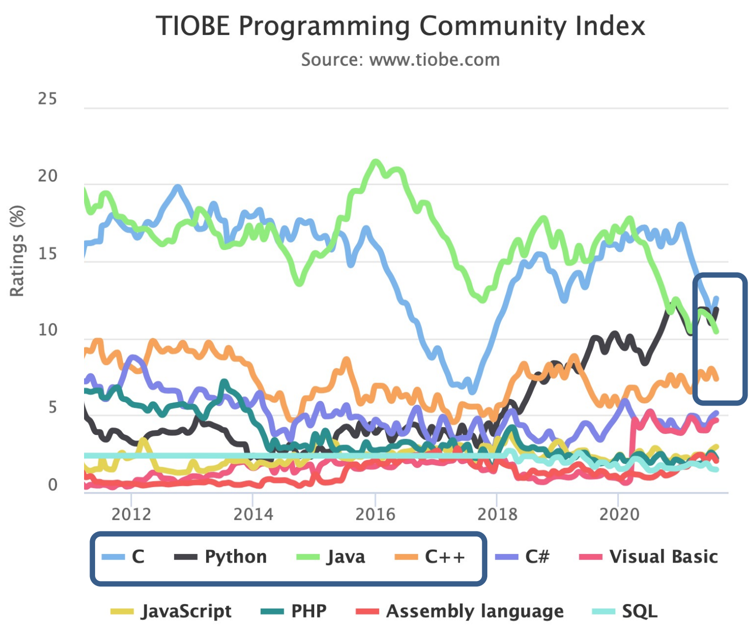
Parallel Programming Models

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

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!

OpenMP Tasking Model

Sequential version

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

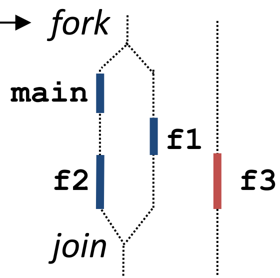
Executes on the host

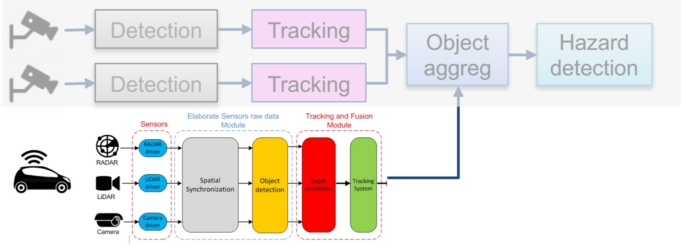
Executes on the accelerator

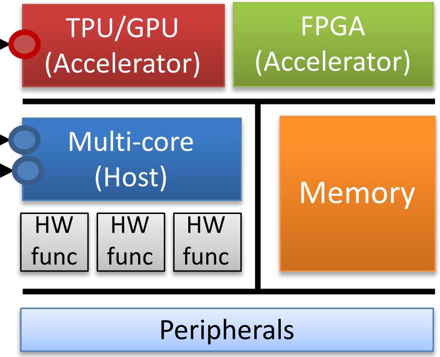
OpenMP version

```
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

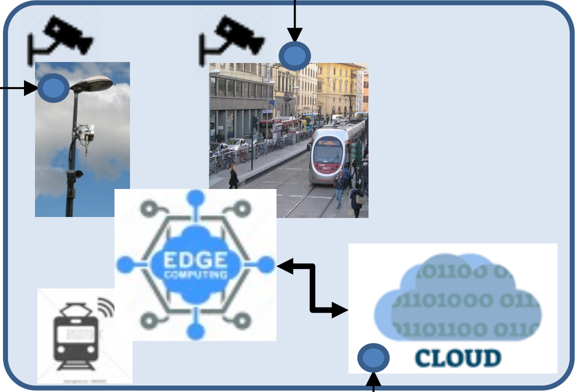
<u>Sequential version</u>

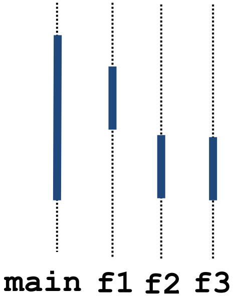
```
def f1():
    …
    return x,y
def f2(x):
    …
def f3(y)
    …
def main():
    x,y=f1()
    f2(x)
    f3(y)
```

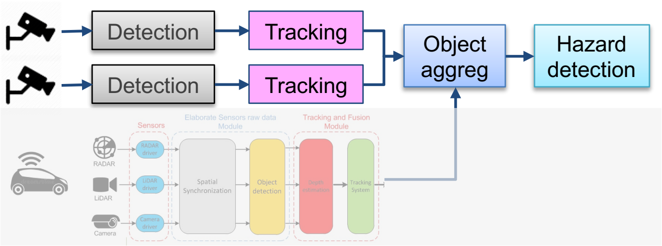
<u>COMPSs version</u>

```
@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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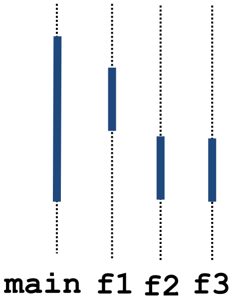
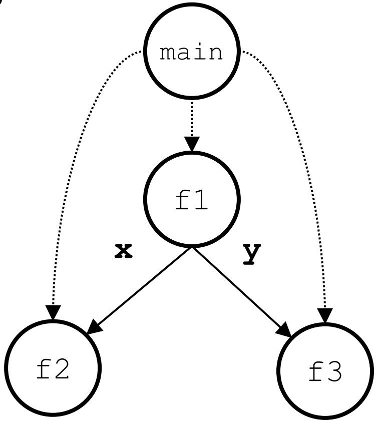
Task Dependency Graph (TDG)

COMPSs version

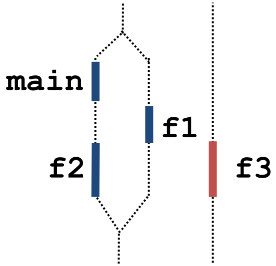
```
@task(x=OUT,y=OUT)
def f1():
    …
    return x,y
@task(x=IN)
def f2(x):
    …
@task(y=IN)
def f3(y)
    …
def main():
    x,y=f1()
    f2(x)
    f3(y)
```





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); }
```

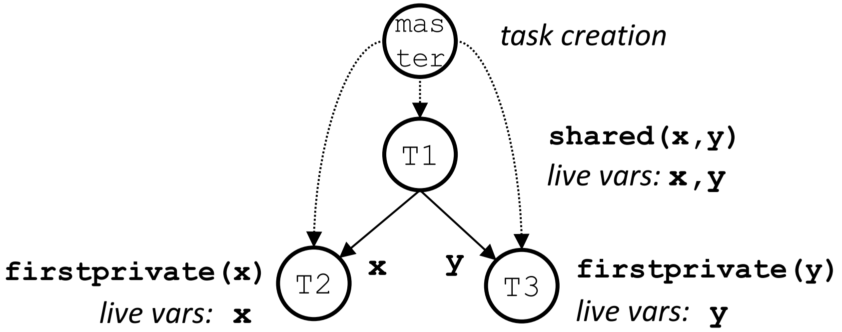


Task Dependency Graph (TDG)

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

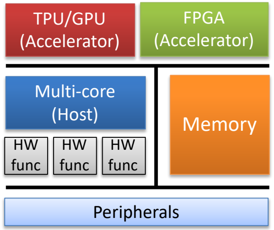
- Tasking provides a great expressiveness to describe the parallel nature of applications
  - It specifies **what** the application does and not **how** it is done
  - The framework is responsible of orchestrating the execution

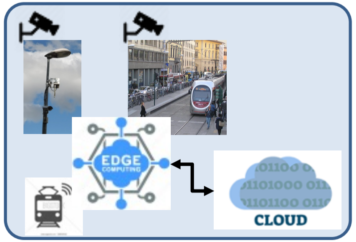
interoperability

OpenMP ⟷ COMPSs

NVIDIA CUDA, POSIX pthreads, RTEMS, AdaCore

MINIO, S3, docker, kubernetes, LITHOPS, Skupper





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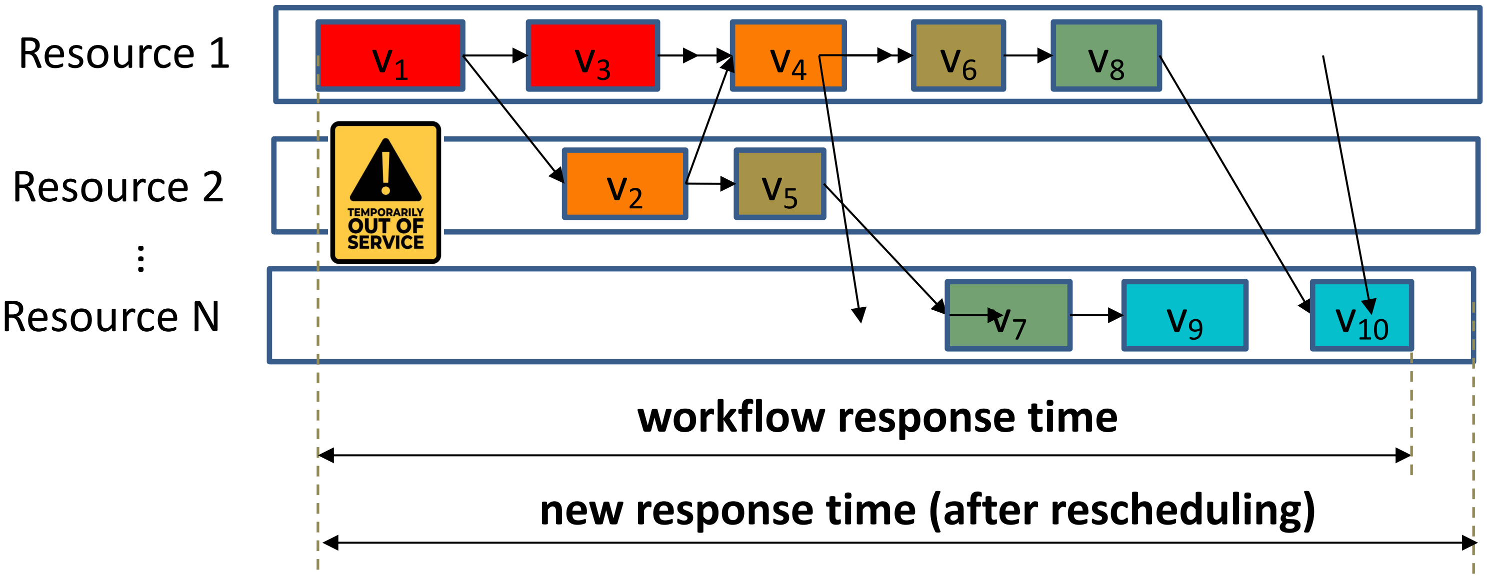
Orchestration of resources



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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