Abstract  In this chapter we offer an overview of microservices providing the introductory information that a reader should know before continuing reading this book. We introduce the idea of microservices and we discuss some of the current research challenges and real-life software applications where the microservice paradigm play a key role. We have identified a set of areas where both researcher and developer can propose new ideas and technical solutions.

1 The Shift Towards Distribution

History of programming languages, paradigms and software architectures have been characterized in the last few decades by a progressive shift towards distribution, modularization and loose coupling. The purpose is to increase code reuse and robustness [17] [29], ultimately a necessity dictated by the need of increasing software quality, not only in safety and financial-critical applications [39], but also in more common off-the-shelf software packages. The two directions of modularization (code reuse and solid design) and robustness (software quality and formal methods: verification/correctness-by-construction) advanced to some extent independently and pushed by different communities, although with a non-empty overlap.
Object-oriented technologies are prominent in software development [53], with specific instances of languages incorporating both the aspects aforementioned (modularity and correctness). A notable example is the Eiffel programming language [47], incorporating solid principles of Object-Oriented-Programming (OOP) within a programming framework coordinated by the idea of design-by-contract, which aims at correctness-by-construction. None of these technologies can nevertheless rule out the need for testing, which robustly remains a pillar of the software development lifecycle.

Other examples exist of languages having a strong emphasis on correctness, both from the architectural viewpoint and in terms of meeting functional requirements [41]. However, until recently, not much attention was dedicated to integrating these principles into a distributed setting winning out properties such as easiness of deployment, a lightweight design and development phase, and minimal need for integration testing. The idea of Microservices [18, 29] and Devops [3, 5, 46] stem out exactly from this widespread and recognized need.

Chapter Outline and Contribution. The contribution of the chapter is twofold, and thus organized in two main sections. Section 2 overviews the essential concepts characterizing the Microservices paradigm, thus serving as introduction for the entire book. Section 3 instead highlights some key research areas in which Microservices applications have gained particular interest and showed some research progress. Conclusions and future works are summed up in Section 4.

2 Microservices

Microservices [18, 24, 29, 49] is an architectural style stemming from Service-Oriented Architectures (SOAs) [37, 55]. According to this architectural style, a system is structured by small independent building blocks – the microservices – communicating only via message passing. The main idea is to move in the small (within an application) some of the concepts that worked in the large, i.e. for cross-organization business-to-business workflow which makes use of orchestration engines such as WS-BPEL (in turn inheriting some of the functional principles from concurrency theory [36]). The characteristic differentiating the new style from monolithic architectures and classic service-oriented architectures is the emphasis on scalability, independence, and semantic cohesiveness of each unit constituting the system. In its fundamental essence, the Microservices architecture [19] is built on a few very simple principles:

- **Bounded Context.** First introduced in [22], this concept captures one of the key properties of Microservices architecture: focus on business capabilities. Related functionalities are combined into a single business capability which is then implemented as a service.
- **Size.** Size is a crucial concept for microservices and brings major benefits in terms of service maintainability and extendability. Idiomatic use of microservices architecture suggests that if a service is too large, it should be refined into two
or more services, thus preserving granularity and maintaining focus on providing only a single business capability.

- **Independency.** This concept encourages loose coupling and high cohesion by stating that each service in Microservices architectures is operationally independent from others, and the only form of communication between services is through their published interfaces.

### 2.1 Microservices vs. Monolith

All the programming languages for development of server-side applications provide abstractions to break down the complexity of programs into modules or components [12, 27, 51]. However, these languages are designed for the creation of single executable artifacts. In monolithic architectures, the modularization abstractions rely on the sharing of resources such as memory, databases and files of the same machine. The components are therefore not independently executable. Figure 1 (reproduced from [45]) shows the classic monolithic organization: the different layers of the system (interface/presentation, internal business logic, and persistence tools) are here split in terms of responsibilities between different modules (the vertical split with numbers from 1 to 4). In fact, each module may take part in the implementation of functionalities related to each layer, the database is common, and so the access to other resources such as memory.

![Fig. 1 Monolith Architecture](image)

Figure 2 (reproduced from [45]) shows the componentization in a Microservices architecture. Each service has its own dedicated persistence tool and communication..
is via message passing. With this organization there is no vertical split through all the system layers, and the deployment is independent. The complexity is moved to the level of coordination of services (often called orchestration [44]). Moreover, a number of additional problems need to be addressed due to the distributed nature of the Microservices approach (e.g., trust and certification [15, 20]).

![Microservices Architecture](image)

**Fig. 2** Microservices Architecture

### 2.2 Microservices vs. SOA

In SOA, services are not required to be self-contained with data and User Interface, and their own persistence tools, eg. database. SOA has no focus on independent deployment units and related consequences, it is simply an approach for business-to-business intercommunication. The idea of SOA was to enable business-level programming through business processing engines and languages such as WS-BPEL and BPMN that were built on top of the vast literature on business modelling [58]. Furthermore, the emphasis was all on *service composition* [35] [21] more than service development and deployment.

### 2.3 Size Matters: The Organization of Teams

A microservice is not just a *very small service*. There is no predefined size limit that defines whether a service is a microservice or not. From this angle, the term “microservice” can somehow be misleading. Each microservice is expected to implement a single *business capability*, in fact a very limited system functionality, bringing benefits in terms of service maintainability and extendability. Since each microservice represents a single business capability, which is delivered and updated independently, discovering bugs or adding minor improvements do not have any im-
pact on other services and on their releases. In common practice, it is also expected that a single service can be developed and managed by a single team [18].

In order to build a system with a modular and loosely coupled design, it is necessary to pay attention to the organization structure and the communication patterns. These patterns directly impact the produced design (Conway’s Law [13]. If a structure is based on the idea that each team work on a single service, then the communication will be more efficient at the team level and in the entire organization. This will lead to an improved design in terms of modularity. Microservices’ approach is to keep teams small and communications efficient by creating small cross-functional (DevOps) teams that are able to continuously work on the same service and to be fully responsible for it (“you build it, you run it” principle [26]).

The teams are organized around services, which in turn are organized around business capabilities [24]. The optimal team size for microservices is best described by Jeff Bezos’ famous “two pizza team” rule, which suggests that the size of a team should be no larger than what two pizzas can feed. The rule itself does not give an exact number, however it is possible to estimate it to be around 6-8 people. The drawback of such approach is that it is not always practical from the financial point of view to maintain a dedicated team of developers for a single service as it may lead to high development/maintenance costs [30]. Furthermore, one should be careful when designing the high level structure of the organization using microservices - increasing the number of services might negatively impact the overall organization efficiency, if no further actions are taken.

3 Research and Applications

Microservices have recently seen a dramatic growth in popularity and in concrete applications [49]. The shift towards microservices is seeing several companies involved in a major refactoring of their back-end systems to accommodate the new paradigm [6, 39]. Other companies just start their business model developing software following the microservice paradigm since day one. We are in the middle of a major change in the view in which software is intended, and in the way in which capabilities are organized into components, and industrial systems are conceived. In this section we describe recent research progress for what concern Microservices applications [45]. It can be structured in the following areas:

- Programming Languages
- Type Checker
- Migration from Monoliths
- Education in DevOps
- Modeling and Self-adaptability
- Real-life software applications with Microservices
3.1 Programming Languages

Microservice systems are currently developed using mostly general-purpose programming languages that do not provide dedicated abstractions for service composition. Current practice is indeed focused on the deployment aspects of microservices, in particular by using containerization. We investigated this issue and made a case for a language-based approach to the engineering of Microservices architectures. We believe that this approach is complementary to current practice. In [28] we discussed the approach in general, and we instantiate it in terms of the Jolie programming language; however the concept is independent from the specific technical solution adopted. Four important concepts have been identified to be first class entities in the programming language in order to address the Microservices architecture:

1. **Interfaces**: to support modular programming, services has to be deployed as black boxes. In order to compose services in larger systems, interfaces have to describe the provided functionalities and those required from the environment.

2. **Ports**: since a microservice interacts with other services, a communication port describes how its functionalities are made available to the network (interface, communication technology, and data protocol). Ports should be specified separately from the implementation of a service. Input ports describe the functionalities that the service provides to the rest of the system, while output ports describe the functionalities that the service requires from the rest of the system.

3. **Workflows**: structured protocols appear repeatedly in microservices and they are not natively supported by mainstream languages. All possible operations are always enabled (for example in Object-Oriented programming). Causal dependencies are programmed by using a book-keeping variable, which is error-prone, and it does not scale when the number of causality links increases. A microservice language should provide abstractions for programming workflows.

4. **Processes**: workflows define the blueprint of the behavior of a service. At runtime a service may interact with multiple clients and other external services, therefore there is need to support multiple concurrent executions of its workflow. A process is a running instance of a workflow, and a service may include many processes executing concurrently. Each process runs independently of the others, to avoid interference, and has its own private state.

3.2 Type Checker

Static type checking is generally desirable for programming languages improving software quality, lowering the number of bugs and preventing avoidable errors. The idea is to allow compilers to identify as many issues as possible before actually run the program, and therefore avoid a vast number of trivial bugs, catching them at a very early stage. Despite the fact that, in the general case interesting properties of programs are undecidable [52], static type checking, within its limits, is an effective
and well established technique of program verification. If a compiler can prove that a program is well-typed, then it does not need to perform dynamic safety checks, allowing the resulting compiled binary to run faster.

In [16] we described and prototyped the Jolie Static Type Checker (JSTC), a static type checker for the Jolie programming language which natively supports microservices. The static type system for the language was exhaustively and formally defined on paper [50], but needed implementation. The type checker prototype consists of a set of rules for the type system expressed in SMT Lib language. The actual implementation covers operations such as assignments, logical statements, conditions, literals and comparisons.

In [56] we integrated dynamic and static type checking with the introduction of refinement types, verified via an SMT solver. The integration of the two aspects allows a scenario where the static verification of internal services and the dynamic verification of (potentially malicious) external services cooperate in order to reduce testing effort and enhance security.

### 3.3 Migration from Monoliths

Several companies are evaluating pros and cons of a migrating to microservices. Financial institutions are positioned in a difficult situation due to the economic climate and the appearance of small players that grew big fast in recent times, such as alternative payment systems, that can also navigate in a more flexible (and less regulated) legal framework and started their business since day one with more agile architectures and without being bounded to outdated technological standards. We worked closely with Danske Bank, the largest bank in Denmark and one of the leading financial institutions in Northern Europe, to demonstrate how scalability is positively affected by re-implementing a monolithic architecture into a Microservices one [6].

Evolution is necessary to stay competitive. When compared with companies (such as Paypal) that started their activities using innovative technologies as a business foundation, in order to scale and deliver value, old banking institutions appear outdated with regards to technology standards. We worked on the FX Core system, a mission critical system of Danske Bank’s software. A key outcome of our research has been the identification of a repeatable migration process that can be used to convert a real world Monolithic architecture into a Microservices one in the specific setting of a financial system, which is typically characterized by legacy systems and batch-based processing on heterogeneous data sources [39].

### 3.4 Education in DevOps

DevOps is a natural evolution of the Agile approaches [33, 4] from the software itself to the overall infrastructure and operations. This evolution was made possible by...
the spread of cloud-based technologies and the everything-as-a-service approaches. Adopting the DevOps paradigm helps software teams to release applications faster and with more quality. DevOps and Microservice Architecture appear to be an indi-
visible pair for organizations aiming at delivering applications and services at high velocity. Investing in DevOps is a good idea in general, and after a migration to microservices it is typically crucial.

As long as DevOps became a widespread philosophy, the necessity of education in the field become more and more important, both from the technical and organis-
tional point of view [11]. The DevOps philosophy may be introduced in companies with adequate training, but only if certain technological, organizational and cultural prerequisities are present. If not, the prerequisities should be developed. We have been deeply involved in recent years in teaching both undergraduate and graduate students at the university, and junior/senior professional developers in industry. We have been also working often with management [46] [5].

3.5 Modeling and Self-Adaptability

Innovative engineering is always looking for adequate tools to model and verify software systems, as well as support developers in deploying correct software. Microservices is an effective paradigm to cope with scalability; however, the paradigm still misses a conceptual model able to support engineers since the early phases of development. To make the engineering process of a microservices-based application efficient, we need a uniform way to model autonomous and heterogeneous microservices, at a level of abstraction that allows for easy interconnection through dynamic relations. Each microservice must have a partial view on the surrounding operational environment (i.e., system knowledge) and at the same time must be able to be specialized/refined and adapted to face different requirements, user needs, context-changes, and missing functionalities.

To be robust, each microservice must be able to dynamically adapt its behaviour and its goals to changes in the environment but also to collaborative interactions with other microservice during their composition/orchestration. At the same time the adaptation must not be controlled centrally and imposed by the system but must be administrated in a decentralised fashion among the microservices.

An important feature of dynamic and context-aware service-based systems is the possibility of handling at run-time extraordinary/improbable situations (e.g., context changes, availability of functionalities, trust negotiation), instead of analyzing such situations at design-time and pre-embedding the corresponding recovery activities. The intrinsic characteristics of microservice architectures make possible to nicely model run-time dependability concepts, such as “self-protecting” and “self-healing” systems [20]. To make this feasible, we should enable microservices to monitor their operational environment and trigger adaptation needs each time a specific system property is violated. To cover the aforementioned research challenges, we already started to define a roadmap [48] that includes an initial investigation on how Domain
Objects [10] could be an adequate formalism both to capture the peculiarity of MSA, and to support the software development since the early stages.

### 3.6 Real-life Software Applications with Microservices

#### 3.6.1 Smart Buildings

Smart buildings represent a key example of application domain where properties like scalability, minimality and cohesiveness play a key role. As a result, smart buildings are an ideal application scenario for the Microservices paradigm. This domain has been investigated with an outlook on Internet-of-Things technologies (IoT) and smart cities [43]. In [54] and [31] it has been shown how rooms of a building can be equipped with devices and sensors in order to capture the fundamental parameters determining well-being and livability of humans, such as temperature, humidity, and illumination. This solution allows to monitor an equipped area and therefore collect data that can be mined and analyzed for specific purposes. The nodes used in this system consist of Raspberry Pi micro-computers [1], Texas Instruments Sensor Tags [2], door sensor and a web camera. Currently, this system is able to collect and analyze room temperature, pressure and illumination level. It is also able to distinguish and count people, which are located in the covered area. The purpose is to monitor and optimize working conditions. The software infrastructure, tightly connected to the hardware, makes use of Microservices to achieve the desired level of scalability, minimality and cohesiveness. Sensors and actuators are connected to a central control panel that is responsible to manage them. At the same time, an automatic Personal Assistant has been designed. It is capable to observe data, learn about different users preferences, and adapt the room conditions accordingly for the different phases of his/her work [32].

#### 3.6.2 Smart Mobility

Organizing and managing the mobility services within a city, meeting traveler’s expectations and properly exploiting the available transport resources, is becoming a more and more complex task. The inadequacy of traditional transportation models is proven by the proliferation of alternative, social and grassroots initiatives aiming at a more flexible, customized and collective way of organizing transport (e.g., carpooling, ride and park sharing services, flexi-buses) [14] [23] [25]. Some of these attempts have been very successful (e.g., Uber), even if in most cases these are seen as isolated solutions targeting specific mobility target groups and are not part of the city mobility ecosystem, mainly based on traditional public and private transport facilities.

An attempt of re-thinking the way mobility is managed and offered is represented by the Mobility as a Service (MaaS) model. MaaS solutions (e.g., MaaS Global:
MaaS (Maas.global) aim at arranging the most suitable transport solution for their customers thanks to cost effective integrated offer of different multi-modal means of transportation. MaaS also foresees radical changes in the business landscape, with a new generation of mobility operators emerging as key actors to manage the increased flexibility and dynamism offered by this new concept of mobility.

People need to travel quickly and conveniently between locations at different scales, ranging from a trip of a few blocks to a journey across town or further. Each trip has its set of requirements. Time may be of the essence. Cost may be paramount, and the convenience of door-to-door travel may be important. In each case, the transportation infrastructure should seamlessly provide the best option. A modern city needs to flexibly integrate transportation options including buses, trains, taxis, autonomous vehicles, bicycles and private cars.

Before changing communities to support what is believed the future transportation will look like and behave, it is necessary to develop mechanisms that allow planners of these localities to model, analyse, and present these possible configurations in ways that the citizens of the communities can understand and participate in.

Coordination for Mobility as a Service can be implemented on a spectrum, ranging from independent services communicating exclusively through market exchanges to hybrid market/hierarchy approaches fixed hierarchical control systems.

Every transportation mean does not need to be a individual competing across multiple markets, but neither should there only be one rigid hierarchy. "Diversity" and "Distributed" selection of the appropriate mean (or a combination of them) is the appropriate compromise respect to say that if one is better than the other, we "kill" the other.

To realize such a "dynamic" and "emergent" behaviors in transportation systems, needs a new way for developing their supporting software systems. In the last years, Collective adaptive systems (CAS) have been introduced and studied by many researchers in different application domains (i.e., Industry 4.0, Logistics, Smart Cities and Mobility, Energy, Biology, etc.). A CAS consists of diverse heterogeneous entities composing a socio-technical system. Individual entities "opportunistically" enter a system and self-adapt in order to leverage other entities’ resources and services to perform their task more efficiently or effectively. At the same time, also collections of entities, called Ensembles, must be able to self-adapt simultaneously to preserve the collaboration and benefits of the system (or sub-system) they are within.

In this very dynamic and rapidly evolving setting, microservices have the potential of offering the right concepts for modeling and for programming smart mobility solutions. Coordination for Mobility as a Services (MaaS) is a mandatory requirement to maintain a certain level of city sustainability (i.e., less CO2 emission, more citizen participation and satisfaction, etc.). It can be implemented on a spectrum, ranging from independent agents communicating exclusively through market exchanges to hybrid market/hierarchy approaches fixed hierarchical control systems.

\[\text{http://www.focas.eu/focas-manifesto.pdf}\]
Our opinion is that instead to implement a selfish mobility we see the need to realize a collective and cooperative mobility where each MaaS provider sees in each single competitor a partner and not an enemy [9]. This domain open new challenges in how distributed microservices, provided by different mobility entities, can be composed dynamically to provide real-time and continuous answers to citizens in a Smart City.

4 Conclusions

The microservice architecture is a style that is increasingly gaining popularity, both in academia and in the industry. Even though it is likely to conduct to a paradigm shift and a dramatic change in perception, it does not build on vacuum, and instead relates to well-established paradigms such as OO and SOA. In [19] a comprehensive survey on recent developments of Microservices architecture is presented with focus on the evolutionary aspects more than the revolutionary ones. The presentation there is intended to help the reader in understanding the distinguishing characteristics of microservices.

We have a long experience in the field of services and business processes [8, 34, 40, 57, 58], including workflows and their reconfiguration [7, 38, 42]. We built on top of this expertise to focus on the active research field of Microservices, and summarized our work in this chapter.

The future will see a growing attention regarding the matters discussed in this chapter, and the development of new programming languages intended to address the microservice paradigm [28]. Object-Oriented programming brought fresh ideas in the last decades, and the expectation is that a comparable shift may be just ahead of us. Holding on the optimism the future is certainly not challenge-free. Security of the microservice paradigm is an issue almost fully untouched [19]. Commercial-level quality packages for development are still far to come, despite the acceleration in the interest regarding the matter. Fully-verified software is an open problem the same way it is for more traditional development models. That said, several research centers around the world have addressed and are addressing all these issues in the attempt to ride the wave and make the new generation of distributed systems a reality.

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