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# Digital Commons as new Infrastructure

## A new generation of public policy for digital transformation

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### Abstract

Free and open source software (FOSS) has come to largely dominate software production. This means that the technology and industry leader of the digital revolution has integrated the digital commons into its core institutional arrangements. To understand the success trajectory of FOSS, however, it is necessary to rethink the initial approaches to the production logic behind it and this new generation of digital commons, recognizing the hybrid and multilayered nature of their governance. A rethink is equally necessary with regard to the public policies applied to FOSS, which have so far failed to successfully engage with these new systems of innovation and production. Especially since we are approaching a new phase of development of the FOSS ecosystem that will be characterized by a greater involvement of the public sector. A review of the notion of infrastructure and an analysis of the design principles emerging in the architecture of the latest generation of digital infrastructures, within which FOSS is increasingly intertwined with standards and modularity, may offer a new perspective to reconsider the construction and governance of these shared utilities and the role of public policy. Following this perspective, the intersection of standardization and FOSS can be identified as the terrain in which a new generation of public policy is most likely to be tested.

Il software libero e open source (FOSS) è arrivato a dominare ampiamente la produzione di software. Questo significa che la tecnologia e l'industria leader della rivoluzione digitale hanno integrato i beni comuni digitali nei suoi assetti istituzionali principali. Per comprendere la traiettoria di successo del FOSS, tuttavia, è necessario rivedere gli approcci iniziali alla logica di produzione dietro di esso e questa nuova generazione di beni comuni digitali, riconoscendo la natura ibrida e multistrato della loro governance. Un ripensamento è ugualmente necessario per quanto riguarda le politiche pubbliche applicate al FOSS, che finora non sono riuscite ad integrarsi con successo con questi nuovi sistemi di innovazione e produzione. Tanto più che ci stiamo avvicinando ad una nuova fase di sviluppo dell'ecosistema FOSS che sarà caratterizzata da un maggiore coinvolgimento del settore pubblico. Una revisione della nozione di infrastruttura e un'analisi dei principi di disegno che emergono nell'architettura delle

infrastrutture digitali di ultima generazione, all'interno delle quali il FOSS è sempre più intrecciato con gli standard e la modularità, può offrire una nuova prospettiva per riconsiderare la costruzione e la governance di queste utilities condivise e il ruolo delle politiche pubbliche. Seguendo questa prospettiva, l'intersezione tra standardizzazione e FOSS può essere identificata come il terreno in cui è più probabile che una nuova generazione di politiche pubbliche venga messa alla prova.

## Introduction

The success of Free and open source software (FOSS) - that is, the surprising development of a phenomenon born in informal communities of autonomous developers on the margins of industry, that has become the standard model for software production - is a phenomenon that has not still been adequately studied and elaborated in economics and political theory ([15]).[1]

The most distinctive feature of FOSS is that it is organized around a commons ([8]; [9]): that is, a resource that is governed by licenses that allow anyone to access, study, use, copy, modify, develop and redistribute it. This characteristic has challenging implications for modes of governance and for forms of generating and appropriating value. However, since FOSS has come to largely dominate software production, this means that the main technology and industry of the digital revolution has integrated digital commons among its main institutional regulations.

Moreover, not only has FOSS emerged in the area of software, but its innovative proprietary solutions have also inspired similar developments in many other domains along with the spread of the digital revolution: with the most interesting developments happening right now in the

1 Indeed the FOSS phenomenon has attracted much interest across multiple disciplines and has inspired many attempts at more general theorizing about the new forms of production emerging with the digital revolution. Initially the main interest focused on the nature of the motivations of developers who were voluntarily contributing to FOSS projects and the new forms of governance emerging in FOSS communities. While theories often framed FOSS as an embryonic model of alternative production. (The literature is extensive. Some significant references may be: [84]; [8]; [63]; [33]; [10]; [102]; [93]). With the ever-increasing entry of market forces, studies have instead focused primarily on the behavior of companies, business models, and the relationships between volunteer communities and companies. More general theorizing has focused on bringing the phenomenon back within conventional neoclassical economic theory, or alternatively on exposing the opportunistic behavior of firms, taking advantage of the voluntary work of communities. (Again the literature is extensive. Some references maybe be: [97]; [68]; [32]; [79]; [27]). However FOSS has continued its expansive march, becoming on the one hand a central terrain of capitalist competition, while on the other hand, as discussed later in this article, it is approaching what should be considered a new phase of its development that will be characterized by a greater involvement of governments. Overall, this evolution calls for new research and further theoretical developments, revising some earlier theorizing, framing the rise of FOSS in parallel with the emergence of new forms of capitalism (see on this, e.g., [61], and [12]), and prospectively - this is the objective of this article – this will require reintroducing in the understanding and governance of the FOSS evolution a much more prominent role of governments.

area of data and hardware. Which shows that the trajectory of FOSS can provide meaningful models for the entire information paradigm ([25]; [80]).

Despite the importance of this evolution, the growth and the trajectory of this phenomenon are still little known and even among scholars and experts its understanding is in the making ([15]).

However, this has not prevented FOSS from becoming a central terrain for capitalist competition on the frontiers of software innovation.[2] Three recent developments give us an idea of the far-reaching changes happening around FOSS. First, Microsoft announced the acquisition of GitHub, the leading platform for FOSS development. Shortly thereafter, IBM bought Red Hat, the largest open source services company, for $34 billion. Finally, the European Commission imposed a spectacular fine on Google for abusing its dominant position in mobile phone technology, which it obtained through its open source Android operating system. Together, these developments also make clear how is necessary to revisit the initial approaches to the production logic behind FOSS and this new generation of commons.

Indeed FOSS, so far, has passed through two quite different stages in the course of its development ([15]).[3] In its first stages, it emerged as a disruptive innovation in communities of developers, triggered by the frustration generated by the expansion of intellectual property rights (IPR) to software, which was perceived by many software developers and researchers as a barrier to their ways of working, their values, freedoms and productivity. Driven by varying motivations - initially not mainly economic - dispersed developers began to come together, forming new types of communities, based on collaboration, voluntary contributions and original forms of governance ([84]; [8]; [63]; [33]). From the very beginning, however, the main innovation introduced by FOSS was around property rights. FOSS licenses in fact work under a regime of what Yochai Benkler termed "open access commons" which makes this kind of commons different from the characterizations, dilemmas and principles of governance that Elinor Ostrom ([78]) developed in her Nobel Prize winning studies. It was indeed this innovation that provided a surprising new anchor that functioned - under certain conditions - as a new institutional arrangement that fostered collaboration and trust, and helped to organize independent and dispersed contributors ([101]). This characteristic has many important implications, both in the modalities of governance and in the forms of generation and appropriation of value ([100]; [75]; [12]). The most relevant is however that this regime denies "the right to exclude" or the exclusive rights of the owner ([30]). With that, it excludes the

2 As will be discussed later in the article, the configurations by which open source has come to play a leading role in competitive strategies within each area of technological innovation may be diverse. But its presence is widespread and its role continues to grow unabated. For example, in AI, Google's Tensor, Facebook's Pytorch and Baidu's PaddlePaddle are based on open source. As it is Baidou's Apollo self-driving car project. In Cloud computing Linux is the most used operating system and many essential components which have become industry-wide standards, like kubernetes, are open source. Open source underpins as such Blockchain technology. In mobile phone, Android and Huawei's new operating system Armony are open source. Open source software is a driving force in IoT and increasingly in the transition to 5G. And so forth.

3 For a more extensive discussion and for a conceptualization of this periodization based on the Multilevel Perspective and the theory of techno-economic paradigms, see [15].

possibility of selling the property or selling the right to access and use the resource, and in this way to appropriate its value, at least privately and exclusively.

Despite this challenging feature, FOSS expanded slowly but surely.[4] And step by step, a growing ecosystem of companies progressively joined or formed around open source projects; and new projects started to be initiated directly by companies. This growth sometimes followed paths that were difficult to imagine at the beginning. Linux, for example, has never succeeded to displace Windows as an operating system for personal computers, as was the initial aim of its developers. But Linux did manage to rapidly become a dominant platform in other areas such as servers and web servers. It was for the latter that Linux began to be used by large organizations with supercomputing needs, like NASA or later Google, exploiting it to build huge and relatively inexpensive data centers and processing capacity ([12]).

Projects that maintain community-centered forms of collaboration continue to exist or emerge. These often informal coalitions continue to contribute significantly to the widespread and accelerated innovation in the digital world ([13]). The same explosion of digital entrepreneurship has largely relied upon FOSS, as the FOSS commons have dramatically reduced barriers to experimentation and prototyping, and have given a tremendous boost to the entrepreneurship and innovation taking place in the startup ecosystem ([39]). Social capital and meritocratic principles are still in place as crucial anchors that regulate the internal functioning of these communities ([9]; [77]). This is also true of the powerful nonprofit foundations that have emerged and have grown up in the FOSS ecosystem ([40]). However, the relationships of most of these foundations, and of the broader FOSS ecosystem, to market forces and corporations have radically changed. Companies have learned to participate and to strategically feed resources back into these communities, influencing these productive environments in different ways. The monitoring and connections have become capillary, increasing the speed and ease with which the most "promising" innovations are picked up, adopted and integrated by venture capital, tech giants, or by industry more broadly.[5]

At the same time, open source adoption has become a laboratory for new kinds of business models and capitalist organizations. Indeed the newest top web companies like Google, Facebook and Amazon would have not emerged or would have not grown so rapidly without FOSS. They have heavily relied on its free resources in their growth and they have deeply engaged with FOSS in their successful - and often "disruptive" - business strategies ([21]; [60]).[6] But they also have been influenced by FOSS in their culture, internal organization and

4 The parable of the GitHub platform, commonly used to host open-source projects (recently purchased by Microsoft for 4 times its last valuation), can effectively summarize the impressive growth of open source. As of November 2021, GitHub reports having over 73 million developers and more than 200 million repositories (including at least 28 million public repositories).

5 A particularly striking example of these dynamics is offered by the case of blockchain technologies. Born and raised in informal networks, then quickly structured around foundations, they were just as quickly adopted by traditional industries, such as banking, logistics or telecommunications, and more recently by governments themselves, such as the Chinese government.

6 In business theory, a disruptive innovation is one that displaces established dominant firms in the marketplace by creating new markets, products, alliances, and value networks. The term was introduced by Bower and Christensen ([21]) and quickly became popular because it describes well the

business models, and have contributed to FOSS development, giving a strong impetus to its expansion ([89]; [12]).

## Reframing new commons

This surprising trajectory sheds new light on the new field of study that has developed around the rediscovery of the notion of the commons, and specifically of the "new commons" or digital commons ([53]). In a sense, it could be argued that while the first wave of commons studies revolved around a definition of the commons as an autonomous sphere distinct from the market and the state, the evolution of FOSS indicates instead the importance of studying how these new commons tend to be governed in hybrid configurations, such as in their interaction with markets ([15]).

Common goods and markets have idiosyncratic institutional forms: if a good is open access, it cannot be appropriated exclusively, nor can it be sold. However, if open source has been absorbed by markets and capitalist competition, it is because commons and markets can not only coexist, but can grow in synergy. This can be explained by observing how the successful inclusion of a commons in a production ecosystem eliminates the market in its domain, but can create, reconfigure or grow adjacent and complementary markets ([12]).

In fact digital ecosystems typically operate on a multi-layered scale, exploiting the existence of "multi-sided markets" ([87]); and all most innovative and successful big techs and platforms providers have increasingly learned to operate through different regimes of value creation and appropriation, adopting and orchestrating at some level or layer in their ecosystem, regimes of shared value and collaborative production ([67]; [12]). Practically, all the most successful companies of the digital age have learned to use these hybrid strategies. The case of Google-Android is a clear example. Likewise Google's condemnation for abuse of dominant position obtained through the open source operating system Android also indicates how these strategies - which include the "decommodification"[7] of critical technological stacks - can be used to achieve new forms of monopolization. Therefore, for example, how necessary is to revisit the conventional Antitrust doctrine ([57]).

strategies that the most innovative and successful companies of the Internet era have followed. As Kevin Kelly ([60]) first intuited - with his famous "follow the free" rule - these strategies have often taken shape through an extensive adoption of FOSS, which has been used, as we will argue below, in different ways to restructure entire economic sectors and shift competition and accumulation to different terrains. Amazon, Facebook, and Google, for example, have widely adopted this FOSS-based "creative destruction" strategy either to dramatically lower structural costs or to completely destroy previous or newly emerging markets.

7 Decommodification refers to a process of removing a good or service from the logic of the market. The term was first introduced to describe the effects of the creation of the welfare state on goods such as education or health care. In the case of FOSS, it is a side effect produced by the introduction of its licenses which guarantee the freedoms (of use, study, reproduction, transformation and distribution) that have been considered from the beginning as constitutive of the Free Software movement and that are recognized by all of the licenses in the FOSS universe.

More broadly speaking, FOSS and new commons are often celebrated because they are open access resources and therefore they greatly democratize productive and cultural environments. However the spread of open source has not prevented the formation of new forms of concentration of power and wealth. Rather, in its current form, it could even encourage its expansion. This is visible by observing the leading role that the giants of the web (Google, Facebook, Amazon, and lastly Microsoft itself) - the same ones that monopolize much of the digital economy - have had and are having in the growth of open source adoption and development ([14]; [15]).

A framework based on three different models can be used to analyze these hybrid arrangements: semi-commons, shared infrastructure and ecosystems creation ([12]).[8] Briefly 'semi-commons' ([92]; [44]) conceptualizes the basic rationale that allows markets and the commons to co-exist and eventually grow in parallel. The concept was inspired by the medieval lands that accommodated two kinds of activities - farming and grazing - carried out at different times of the year; as well as two different regimes of property - commons and private properties. It allows to visualize a two-tiered framework based on the co-existence of a double regime of property and economic activity in the same system of resources. This framework can house the variety of 'open business models' emerged around FOSS: sale of services, support, certifications, the development of 'freemium' offers, the integration of property additional software features ([52]; [81]). Whatever the differences among these models the structure is the same: the core software remains a commons, that cannot be appropriated in an exclusive way. But on top of this shared base, different forms of commercialization and markets can be devised or generated.

This two-tiered structure sustains also the rationale that is most used for explaining companies' adoption of FOSS: 'shared infrastructures' ([79]; [46]). In such cases market actors are better framed as users or buyers of software, rather than producers and vendors of software. For these actors, FOSS, as a commons, provides a way to share and economize on the costs and risks related to the access to and use of necessary components of production. Although these forms of collaborative "decommodification" are far from easy to achieve, the sharing of resources is made easier by leveraging certain characteristics of the digital commons, such as its non-rivalry in use and practically non-existent marginal costs ([86]). The dominance that Linux achieved in servers or cloud computing are examples of this use of FOSS to build shared infrastructure. At the same time, the extremely concentrated structure of the cloud computing market shows, once again, how FOSS can go hand in hand with new forms of market concentration.

If semi-commons explains the basic logic, and shared infrastructure is the most widespread reason behind the adoption of FOSS by market players, the third term - 'the generation of ecosystems' ([74]; [55]) - highlights how FOSS, as a commons, has been used to implement innovative capitalist competition strategies. Google's Android represents the clearest and most successful example ([83]). This strategy is based on a multi-layered modulation of ownership regimes and consists of disrupting a market by "decommodifying" a crucial layer of an industrial ecosystem: in the case of Android, the operating system used by the mobile phone industry. In this case, the objective is to shift competition in an industry into a more

8 For a broader discussion of this framework see: [12].

advantageous terrain; to attract users, developers and various types of business ecosystems to a new standard, infrastructure or platform; and to exploit the growth or creation of complementary markets, which are adjacent to and correlated with the FOSS commons ([12]). "Surveillance capitalism" ([103]) which revolves around the hoarding and exploitation of user data, has been a fertile ground for these strategies. As the recent fine imposed on Google by the EU Commission shows, these cross-subsidy practices can be used as a kind of innovative dumping strategy, which aims to eliminate competitors, trigger adoption and various types of network effects, and achieve monopolistic positions.

However, if we take a look at all the frontiers of software innovation (Cloud computing, AI, IoT, Data analytic, DLT, even 5G and Quantum computing), we can see this repertoire of FOSS strategies at work: with large technology companies trying to create ecosystems around their own platform or standard; or with an ocean of startups exploring new possibilities at the frontiers of innovation by building on the availability of a large amount of open access resources generated by previous FOSS development cycles; and in other cases with hundreds or even thousands of companies converging - often under the umbrella of a FOSS foundation - in the development of a common infrastructure.

And if we were to try to summarize what we can learn from the trajectory that FOSS has experienced so far: the ability to move in production environments made of multi-level integrated systems operating through different regimes of ownership, governance and value generation and appropriation ([56]), is one of the important lessons that we can draw from the trajectory of open source and its adoption in the market ([15]).

## The necessary innovation in public policy

A re-apprehension of FOSS is similarly necessary with regard to public policy and public sector, which have so far failed to successfully engage with open source ([14]).[9]

The reasons for public administrations to support the use and development of FOSS are manifold and are both economic and political, as FOSS promises to reduce costs and risks and increase independence and transparency in critical resources, services and infrastructure ([20]).

However, while the transition to FOSS in the market is consolidating, public administration and public policy are still struggling to find a way to productively engage with this new model of technology development and production and exploit its many potentials.

There has been no lack of attempts. Rather, public policy that promotes FOSS began early and has been widespread. The Center for Strategic and International Studies (CSIS) classified the public policy initiatives supporting FOSS in four categories: research, mandatory (cases where the use of open source software was required), preference (where preference was given to open source), and advisory (where the use of open source was simply authorized) ([69]).[10] According

9 For a more extensive discussion of public policies applied to FOSS, their trajectory and characteristics, their limitations and more recent trends, see [14].

10 Another type of classification can be found in Bouras et al., who made a summary of FOSS policy

to the available data, there have been hundreds of public administrations that have announced and/or implemented policies aimed at adopting or promoting FOSS at many different levels ([69]).[11] However, the results of these policies have been disappointing.

Barriers to widespread adoption of FOSS in public administrations have been many ([95]; [72]; [98]; [82]). But trying to draw some lessons, it can be argued that public policy has underestimated the complexity, integration, and dynamic evolution of these technological systems. It has not understood or addressed the obstacles generated by the lock-in mechanisms arising from the integrated ecosystems created by proprietary hardware and software manufacturers around their technology platforms. And it has not solved the limits produced by the fragmentation of alternative solutions based on open source (a typical weakness of open source dynamics), which instead public administrations have often paradoxically contributed to aggravate ([14]).

More generally, neoliberal political orientations that prescribe public policy and the public sector to abstain from pretending to guide and direct technological development and on the other hand, the individualistic and libertarian spirit of the original FOSS communities have both discouraged to properly rethink the possible role of governments and public policies in these new productive environments.

In sum, no clear successful model has emerged; and there have been numerous setbacks.

Nevertheless, if in its early days FOSS was a laboratory for social innovation and later a catalyst for market innovation, there is good reason to think that important experiments and innovations in public policy will emerge around this phenomenon. And further that one of the most important areas of innovation in the next evolution of the FOSS ecosystem could come precisely from greater public sector involvement.

More specifically, we can try to glimpse the possible contours of a renewed role for public policy in these new environments of innovation and production through a twofold

recommendations in the European Union context. They identified in literature 25 recommendations which they organized into five areas: 1) data openness and reusability; 2) licensing, procurement and software market policies; 3) FOSS adoption, integration and sustainability; 4) Research and innovation; 5) Training and education ([20]).

11 Advocacy for the adoption of FOSS in public policy and public administration began early, around the beginning of 2000s; and– contrary to popular belief– there have been a significant number of attempts to put forward a FOSS agenda in public policy. The Center for Strategic and International Studies (CSIS) published until 2010 an annual report on "Government open source policies" and maintained a database of open source policy initiatives worldwide, taken at different levels of government. According to these surveys, the first policies appeared in 2001 and in its last version, the database counted a total of 364 open source policy initiatives worldwide ([69]). Since the CSIS stopped collecting data, there has not been any center that has globally and systematically gathered this kind of information. For Europe the best available source of information is the Open Source Observatory and Repository (OSOR), an EU-funded information center which seeks to circulate and account for initiatives in the EU. Globally, the platform GitHub has become a new source of information: since it is the platform where most FOSS development takes place, some research has analyzed the presence of public sector actors on the platform.

reconsideration: a better understanding of the FOSS trajectory and a revisiting of the notion of infrastructure.

## Revisiting the notion of infrastructure

There is no precise definition of infrastructure ([37]). Moreover, as in other areas, the digital revolution is encouraging a new look at this concept.

In economic terms, the notion of infrastructure is usually associated with essential or basic systems, with goods and services of general utility necessary for the functioning of society as a whole. This is also the main reason why infrastructures have mostly been considered as not suitable to be provided and managed by a pure market logic, and have been associated with some kind of public intervention, either through direct control and ownership or through regulation, in order to ensure the cheapest, most universal and non-discriminatory access possible to both market actors and citizens. Moreover, these essential systems of general utility, especially when provided by networked infrastructures, tend to benefit from network effects and generate monopoly or quasi-monopoly conditions, thus providing a potential exorbitant power over the entire universe of activities. For these same reasons, infrastructures are often associated with certain characteristics of public goods, as for example with "synergies" and "positive externalities," which as such cannot be fully appropriated by providers ([88]; [94]; [48]).

The growth of informationalism as a new development model, however, relies on very different types of infrastructure than those of the industrial era. It is not just physical infrastructure, such as cables, web servers, hardware or data centers, but also infrastructure made, for example, of software, protocols, data, standards, operating systems, and programming languages. More importantly, it is the increasingly pervasive and ubiquitous intermediation of digital networks and data flows that is contributing to potentially expanding and blurring the scope of the notion of infrastructure, even more so because of the increasing interconnection and interoperability that is becoming a necessary requirement among all information systems and devices. The result is an increasingly intricate and interdependent complex of multilayered infrastructures that opens up great challenges in terms of both understanding and governance.

Some have observed, in the light of the OpenSSL case, a famous case of systemic vulnerability in a FOSS program which affected millions of organizations, that "the current state of our digital infrastructure is one of the most poorly understood problems of our time" ([39]).

Indeed, FOSS provides an essential part of this intricate system and will increasingly do so in the future. And the complex requirements of producing and managing these new infrastructures have been one of the reasons that have contributed to the industry's increasing reliance on shared protocols, standards, and software; or that the logic of sharing and collaborating, rather than exercising exclusive forms of ownership, has spread as a less risky, more viable, robust, and efficient solution ([24]; [86]). On the other hand, it can be argued that it is these same characteristics that have allowed innovative forms of informational

capitalism to disproportionately capitalize monetarily on the value that is co-produced and shared by large ecosystems ([73]), through control of key points and layers or "bottlenecks" ([7]) in these intricate networks of flows and shared infrastructure.

So far the different waves of innovation created by the digital revolution have generated what has been described as an "accidental megastructure": a stratified complex infrastructure emerged without a grand plan ([22]).

Nonetheless, along with the "maturation" of the new techno-economic paradigm ([80]), we are approaching a new inflection point. A cluster of new interconnected "general purpose" ([34]) or "enabling" ([96]) technologies is emerging, which announce and is going to deeply shape a widespread process of "digital transformation" and "datafication" across society. And the geopolitical competition which is breaking out around the control of these tightly integrated technologies signals that this time the design and deployment of these digital infrastructures will be marked by both a return of a more deliberate political design and a stronger public intervention.

China's astonishingly rapid rise on the frontiers of technological innovation and its governing model of industrial technological development have certainly played a crucial role in transforming the orientation in both Europe and the US ([59]; [70]; [90]). Equally important has been the recognition of the central importance of data in the advancement of the latest generation of algorithms ([66]) and future value chains across all economic sectors ([43]).

In this shift, Europe is an emblematic case. In the space of a few years - with the pandemic acting as an accelerator - Europe has radically changed its approach in digital and technological policy ([42]). The slogan that sums up this change in EU policy is "digital sovereignty" ([31]).[12]

Indeed the reasons for the "Polanyi moment" we are experiencing and which is bringing back the rediscovery of the necessary role of the State in this historical conjuncture are manifold. Equally multifaceted are the political controversies and necessity of new regulations that are mounting around the digital sphere.

Nonetheless, the awareness of the far-reaching impact and long-term consequences of the deployment of this superordinate layer of new techno-infrastructure is certainly a crucial factor. As is the increased awareness that its development and deployment will produce a further convergence, integration and profound restructuring of all previously separate technological and productive systems ([7]; [96]).

12 At the European level, initiatives in the digital field overlap with great speed. In 2021 alone, limiting simply to cloud computing, four different initiatives have been launched: Gaia-X; the European Alliance for Industrial Data, Edge and Cloud; the Horizon Cloud coordination; and, above all, the IPCEI (Important Projects of Common European Interest) on the new generation of cloud and edge infrastructures.

## A new emerging matrix

This juncture is occurring significantly at a time when FOSS is reaching its "momentum" ([54]). Not only because it is spreading along all these new technological frontiers, but because it is more broadly beginning to overthrow the dominance, lock-in mechanisms, and broader "path dependence" ([35]) that have long operated in favor of proprietary software in several dimensions: such as, for example, accumulated investment, industry structure, technical design and compatibility, cognitive and behavioral patterns and routines, or (though still lagging) public regulations and programs ([14]).

But a closer look at the latest generation of digital infrastructures (e.g., Cloud computing, Internet of Things, Artificial Intelligence) also highlights an innovative and more multifaceted matrix that is increasingly shaping their architecture and design. It is organized around three principles: FOSS, standardization and modularity.

A significant manifestation of the prominence that this matrix has achieved is interestingly offered by the recent declaration of the European Council on the Digital Society, where these three principles are explicitly named, and public administrations are urged to use them as a lever to achieve sovereignty and interoperability in Europe's digital systems ([31]).

While these three principles and approaches to technology development are by no means new, what is new and remarkable is the prominence they have gained in recent decades with the ICT revolution and globalization, and even more so is their increasing intertwining in the actual practice of technology development.

The literature has dealt extensively with each of these phenomena. And behind the prominence gained by each of these principles, a diverse set of forces has operated. For example, globalization and ICT have placed increasing emphasis on standards ([76]; [91]). Modularity has grown associated with the expansion of outsourcing practices (Baldwin et al. 2000). Equally complex are the forces that have led to the gradual expansion of FOSS, first in developer communities and then in industry, ranging from the nonrival nature of digital information ([2]; [11]; [45]; [86]), to the characteristics of immaterial labor ([65]), to the emergence of new forms of capitalist competition ([60]; [12]).

There is also a growing body of literature that is exploring the connections between these different approaches - more typically between two of them, for example, standards and FOSS ([18]) or FOSS and modularity ([62]) - and how they are mutually influencing their own evolution. However, there is still a lack of studies that approach these principles as elements of a single emerging matrix that is increasingly shaping the design and management of complex, large, and interdependent technology systems.

Instead we can gain useful insights by considering them in this way.

Considering it as a recombinable set of principles, in fact, it is possible to see the emergence of this institutional and architectural matrix as a response to the unprecedented pace of innovation, evolution, complexity and interdependence that has increasingly characterized digital technological systems. More precisely, they can be seen as a set or repertoire of solutions

that have been used to manage a fundamental tension between two contradictory needs that have shaped the digital revolution and its expansion. On the one hand, the need to provide stable references to facilitate specialization, division of labor, and rapid adoption and integration of new solutions and developments (i.e., "scalability"). On the other hand, the need to maintain maximum flexibility in order to enable agile experimentation and innovation, as well as greater resilience to destabilizing or "disruptive" changes.

Furthermore, looking at the diverse literature that has been developed around these principles, if we were to try to extract a common rationale, there are two general rationales that are most used to justify and explain the adoption of each of these design rules separately: simplify complexity management and reduce communication and transaction costs ([5]; [11]; [17]). In a sense, this allows this matrix to be understood as consisting of a family of strategies that address the daunting complexity and enormous transaction costs implicit in the development of these new dynamic techno-infrastructures, without trying to return to the old solutions - the use of vertical, integrated, and planned forms of hierarchical organization - that were typical of the Fordist era ([28]; [26]).

On an another level, it would be interesting to explore the connections between the increasingly widespread use of this matrix and the rediscovery of the predominantly recombinatorial nature of innovation ([91]; [64]; [4]), including its ambivalent relationship with standardization ([51]; [49]).

On the other hand, in economic terms, there is instead a fundamental challenge and trade-off that has been widely discussed by literature in relation to each of them: which is that each of these ways of organizing complex systems of innovation and production, in different ways reduces (standards, with the obvious exception of proprietary standards), threatens (modularity, with the case of the computer industry - the first to adopt a broad modular architecture - as the most debated case) or completely undermines (FOSS) the ability to privately appropriate and "capture" value through intellectual property rights ([6]; [11]; [17]).

The mechanics through which this outcome is achieved or can be countered - that is, the possible countermeasures or solutions to obstacles to private appropriation of value - can be different in each case. But the trajectory of FOSS that we have described in the previous sections suggests that, crucially, once again this feature can be differently distributed among different actors using the layered design of configurations that the application of the three principles of the matrix allows. For example, these architectural principles can be modulated to deploy on different levels, regimes of standardization and monopoly as opposed to spaces of innovation and competition, or under other terms, levels controlled by systems of intellectual property rights and levels managed as shared commons with open access. This is precisely the strategy that Google applied in the case of Android. Furthermore this architectural flexibility is highly enhanced by the digital nature of these infrastructures themselves ([45]).

The architectural design of apps and platform ecosystems ([50]; [29]) exemplifies well how this matrix works and how the layered modulation of its principles can produce, for example, a disproportionate concentration of the control on "monetized" markets as opposed to "decommodified" and shared layers ([12]; [73]). Just as these same design principles can

structure a hierarchy of layers that combines more stable central blocks (the platforms) that provide elements of stability and simplify innovation and the management of variability at other levels (applications). The important and productive role that the more stable elements play should not be overlooked ([74]; [71]; [51]). In fact, it is these components that greatly simplify innovation within the ecosystem that is aggregated around these core elements (platforms), accelerating the adoption and scalability of new features and services (applications). Similarly, although in principle innovation continues to operate at all levels, the ability of these more stable structures, once established, to resist change and displacement - through a variety of lock-in mechanisms that begin to operate - and instead largely influence technological trajectories ([36]) and the economic regimes that can be built upon them, should not be overlooked.

## A new approach to standardization

Let's summarize the path followed so far. We have seen how FOSS has scaled up until arriving at sitting at the center of software industry and development. This occurred critically through its adoption by industry and in market competition. Following this trajectory, we have argued about the necessity to revisit in various ways the understanding of this phenomenon and we have synthesized one first lesson: the importance of the ability to move in production environments made of multi-level integrated systems operating through hybrid regimes of ownership, governance and value generation and appropriation.

We have then argued that this revisitation is even more necessary when addressing the relation between FOSS, public policy and public sector, for the substantial failures of the policies which have been so far attempted. Even more so since we are approaching a predictable entrance of the public sector in this ecosystem. The fundamental reason of this predictable entrance is that FOSS "momentum" coincides with a point of inflection of the digital revolution and the coming to maturation of a new generation of techno-infrastructures, which are going to shape in depth the transformation of our society.

Looking at the emergence of this new generation of techno-infrastructure, we further highlighted the rise of a new matrix of design principles, in which FOSS is increasingly combined with two other principles: modularity and standardization. We suggested that the rise of this matrix reflects the structural conditions that characterize the development of these technological systems, such as the need to simplify the management of their complexity, scale, scope, and dynamism, and to meet contradictory requirements such as providing flexibility and stability at the same time. Furthermore, we have argued that this matrix helps to clarify an additional layer in the emerging governance models of these large, complex and integrated technical systems. This level in turn can be used for a differentiated distribution of some challenging consequences that are brought about by the application of this same matrix: namely, the reduction of transaction costs and risks, the promotion of shared synergies along with important limits placed on private appropriation.

We can now get back to the point, and without claiming to sketch the full range of innovations

that might characterize the next phase of evolution of the FOSS ecosystem with the foreseeable entry of governments, we can try to identify the most likely site where this entry is about to begin.

That site is the standardization processes.

If we look at the evolution of the ICT international system of standardization over the past few decades we can observe further elements that corroborate this trajectory and the critical relation that is emerging between standardization and FOSS ([18]). Standards setting and standard wars, in fact, have gained ever more prominence in the governance of the systems of technological innovation and development ([91]). At the same time, the traditional recognized international Standard developing organizations (SDO) have been increasingly displaced by new standardization strategies, whether simply pursued by market forces and private consortia or organized by a proliferation of new competing Standard setting organizations (SSO). In software, however, it is FOSS itself that has progressively emerged as an outsider and unexpected protagonist in the international standardization scene. On one side, major technology companies have learned to use FOSS to penetrate certain layers of software and impose *de facto* standards to generate ecosystems around their platforms and exploit their competitive advantages in collateral markets. In other cases, instead, communities and companies have teamed up to develop common standards, creating a sort of embryonic new typology of standards-setting organizations, which have grown in importance, as with the fairly impressive role that the Linux Foundation has come to play in the global technology industry, in which it emerged as a consolidated leader in the governance of shared industry-wide projects. While in parallel the most modern SDO (e.g. W3C and IETF), focused on web technologies, have increasingly adopted "open source" practices ([23]), in their Intellectual property policies, and in their "open standards" procedures (open, transparent process and documentation and consensus-based decision-making).[13]

More in general, at this stage of the digital revolution, standardization is emerging as one of the most critical areas of governance. Even more so, because the implications and scope of a new approach to "governance through standardization" go far beyond just technological or economic aspects ([14]). With good reason, standards have been equated with the building blocks of information infrastructures ([47]), have been described as a social technology ([38]) and have been even compared to institutions ([16]). But more practically, if we look at all frontiers of digital innovation, the lack of common standards is probably one of the main obstacles to actually deploying their potential in terms of systemic productivity leaps ([35]; [80]). To think that this transition can be governed by simple market logic seems both unrealistic and untenable. Rather a more active participation of governments not only seems inevitable for political reasons, but is increasingly being called for by private industry itself. And an evolution in this direction also allows us to glimpse a path through which to rediscover a "productive" function of the public actor in new forms.

Yet in general standardization has been quite neglected by public policy. Moreover, privatization, deregulation, and neoliberal policies, along with accelerating technological and

13 For an early discussion of the relationship between open source and open standards, see [1].

economic change, have progressively marginalized national standardization agencies and the public sector. And at present, public administrations lack the necessary skills, flexibility and speed, as well as the incentives and resources required to provide adequate governance for these processes.

Unquestionably, reversing this trend will be a difficult process. Even more so, because of the scale and complexity of the next generation of digital technology systems and the diversity of actors and ecosystems that will be integral to their development and management.

To be sure, new governance models will be needed to regain the ability to steer the development and management of the next generation of infrastructure. For what we have argued, we can outline some of its characteristics. A new generation of public policy will have to learn to combine different regimes of ownership, governance, and value generation and appropriation. That is, to manage a new kind of mixed political economy. Along with this, it will have to learn to manage a new kind of "tripartite system of governance," consisting of governments, markets, and communities. And learn how to compensate for the relative shortcomings and failures of each of these systems. Finally, it will need to pay particular attention to the design of the architecture of these systems, developing new governance methods based on the mix of FOSS, standards, and modularity, in order to provide both the necessary elements of stability and standardization, designing them in a way that is as resilient as possible, and the equally necessary spaces for experimentation and innovation and the growth of new markets.

Overall, a long and difficult path, indeed. However, we can be quite confident about where these innovative practices involving governments themselves will initially be tested. It is around the intersection of standardization and FOSS.

What's more, it is probable that a significant portion of future global political, economic, and technological competition will take place around this area of innovation in the systems of governance.

The first signs have already appeared. And as it has happened many times in the development of FOSS, the first to bet on its potential are the competitors at a disadvantage. That is, in this case, China and the European Union. Both have begun to move along the trajectory we have outlined. Both have begun to outline an ambitious agenda on the frontiers of digital innovation that we have referred to in this article, with the dual purpose of gaining new spaces of "sovereignty" and opening up new avenues of development. In both cases, these programs combine a strategic use of standardization ([41]; [18]; [70]; [90]) with an equally strategic recognition of the need to incorporate and adopt FOSS into their innovation and technology policy ([19]; [3]).

In this context, Europe has outlined perhaps - for the first time in the digital era - the most interesting initiatives. Not only, in fact, as we noted, the Berlin Declaration of the EU Council on the Digital Society makes explicit reference to FOSS, standardization and modularity in its strategy, urging public administrations to exploit its potential. But more concretely, Gaia-X, the recently born European initiative that focuses on defining FOSS standards across certain data

layers and cloud infrastructures - initially promoted by the German government and rapidly evolving into a Europe-wide foundation, officially supported by multiple European governments - represents perhaps across the global landscape, the most interesting innovation that has emerged along the very lines we've outlined here.

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