
















# Foundational Competencies and Responsibilities of a Research Software Engineer

Heidi Seibold <sup>1</sup> Florian Goth <sup>2</sup> Jan Linxweiler <sup>3</sup> Jan Philipp Thiele <sup>4</sup>  
Jeremy Cohen <sup>5</sup> Renato Alves <sup>6</sup> Samantha Wittke <sup>7</sup> Jean-Noël Grad <sup>8</sup>  
Fredo Erxleben <sup>9</sup> Magnus Hagdorn <sup>10</sup> Harald von Waldow <sup>11</sup>  
Moritz Schwarzmeier <sup>12</sup> Matthias Braun <sup>13</sup> Simon Christ <sup>14</sup>  
Gerasimos Chourdakis <sup>15</sup>

November 15, 2023

---

**Abstract:** The term Research Software Engineer, or RSE, emerged a little over 10 years ago as a way to represent individuals working in the research community but focusing on software development. The term has been widely adopted and there are a number of high-level definitions of what an RSE is. However, the roles of RSEs vary depending on the institutional context they work in. At one end of the spectrum, RSE roles may look similar to a traditional research role. At the other extreme, they resemble that of a software engineer in industry. Most RSE roles inhabit the space between these two extremes. Therefore, providing a straightforward, comprehensive definition of what an RSE does and what experience, skills and competencies are required to become one is challenging. In this paper we define the broad notion of what an RSE is, explore the different types of work they undertake, and define a list of fundamental competencies as well as values that define the general profile of an RSE. On this basis, we elaborate on the progression of these skills along different dimensions, looking at specific types of RSE roles, proposing recommendations for organisations, and giving examples of future specialisations. An Appendix details how existing curricula fit into this framework.

**Keywords:** research software engineering, curriculum design, training, learning, competencies, certification

---

## Contents

<b>1</b>	<b>Introduction</b>	<b>2</b>
1.1	Terminology . . . . .	3
<b>2</b>	<b>Related work</b>	<b>4</b>
<b>3</b>	<b>Values</b>	<b>5</b>
3.1	Current challenges . . . . .	5
3.1.1	Handling of data and personal data . . . . .	5

---

<sup>1</sup>IGDORE Munich, Germany

<sup>2</sup>Institute for Theoretical Physics and Astrophysics, University of Würzburg, Germany

<sup>3</sup>Technische Universität Braunschweig, Germany

<sup>4</sup>Weierstrass Institute, Berlin, Germany

<sup>5</sup>Imperial College London, London, UK

<sup>6</sup>European Molecular Biology Laboratory, Heidelberg, Germany

<sup>7</sup>CSC – IT Center for Science, Espoo, Finland

<sup>8</sup>Institute for Computational Physics, University of Stuttgart, Germany

<sup>9</sup>Helmholtz-Zentrum Dresden-Rossendorf, Germany

<sup>10</sup>Charité Universitätsmedizin Berlin, Germany

<sup>11</sup>Johann Heinrich von Thünen Institute, Centre for Information Management, Braunschweig, Germany

<sup>12</sup>Mathematical Modeling and Analysis, TU Darmstadt, Germany

<sup>13</sup>Cluster of Excellence IntCDC, University of Stuttgart, Germany

<sup>14</sup>Leibniz University Hannover, Department of Cell Biology and Biophysics, Computational Biology, Germany

<sup>15</sup>School of Computation, Information and Technology, Technical University of Munich, Garching, Germany

3.1.2	Mentoring and diversity . . . . .	5
3.1.3	Shaping digital science . . . . .	5
3.1.4	Emerging challenges . . . . .	5
<b>4</b>	<b>Required generic RSE skills</b>	<b>6</b>
4.1	Software engineering skills . . . . .	6
4.1.1	Creating documented code building blocks (DOCBB) . . . . .	6
4.1.2	Building distributable libraries (LIBS) . . . . .	6
4.1.3	Adapting to the software life-cycle (SWLC) . . . . .	6
4.1.4	Use repositories (SWREPOS) . . . . .	6
4.1.5	Software behaviour awareness and analysis (MOD) . . . . .	7
4.2	Research skills . . . . .	7
4.2.1	Curiosity (NEW) . . . . .	7
4.2.2	Understanding the research cycle (RC) . . . . .	7
4.2.3	Software re-use (SRU) . . . . .	7
4.2.4	Software publication (SP) . . . . .	7
4.2.5	Using domain repositories/directories (DOMREP) . . . . .	7
4.3	Communication skills . . . . .	7
4.3.1	Working in a team (TEAM) . . . . .	8
4.3.2	Teaching (TEACH) . . . . .	8
4.3.3	Project management (PM) . . . . .	8
4.3.4	Interaction with users and other stakeholders (USERS) . . . . .	8
4.4	RSE tasks and responsibilities . . . . .	8
<b>5</b>	<b>How much do different people need to know?</b>	<b>9</b>
5.1	Career level . . . . .	9
5.2	Helpful RSE skills for researchers in an academic career . . . . .	12
5.3	Project team structures . . . . .	13
<b>6</b>	<b>RSE specialisations</b>	<b>17</b>
6.1	Specialisations within the core RSE competencies . . . . .	17
6.2	Specialisations outside the core RSE competencies . . . . .	17
<b>7</b>	<b>Future work</b>	<b>18</b>
<b>8</b>	<b>Conclusion</b>	<b>19</b>
	<b>Acknowledgements</b>	<b>19</b>
<b>A</b>	<b>Appendix</b>	<b>20</b>
A.1	An example master's programme for research software engineering . . . . .	20
A.2	An example of a possible career path . . . . .	21
A.3	Existing frameworks . . . . .	22
A.3.1	HPC skills and certification . . . . .	22
A.3.2	Bioinformatics skills and certification . . . . .	22

# 1 Introduction

Computers and software have played a key role in the research life-cycle for many decades, while they are now vital elements of the research process across almost all domains. They enable researchers to collect and process ever-increasing amounts of data, simulate a wide range of physical phenomena across previously unexplored scales of the universe, and discover previously inconceivably complex structures in nature and societies via machine learning. This prevalence of computations in research means that basic software skills are now required by researchers at all career levels, and in fields significantly beyond the previously expected. Research software is now used and developed not only in science, technology, engineering and mathematics (STEM) domains, but also in medicine and in digital humanities.

Researchers often lack the skills to use specialised software for their research, let alone write it [65]. If they come from a non-technical domain, they may also struggle to know what to ask when trying to request help

from and interact with more experienced staff at their institutions. A gap still exists in academic education, as many curricula do not sufficiently prepare their students in this regard. This situation is exemplified by the extracurricular MIT class “The Missing Semester of Your CS Education” [59], which aims to convey computing ecosystem literacy even to students of Computer Science at MIT.

Researchers investing increasing amounts of their time developing their software engineering (SE) skills to support their research work can find themselves with little time to do the research itself. This, in turn, presents career development challenges since the experience required to gain and progress in research and academic roles is traditionally assessed through metrics that do not directly include software outputs. A recent shift towards the establishment of the distinct role of a “*Research Software Engineer*” [41] (RSE, a term that emerged from the UK a little over 10 years ago [28]), now provides a base on which sustainable career opportunities can be (and are being) built, allowing for better training of researchers and more effective support for the development of high quality research software. There is still a long way to go, but positive change is well underway.

RSEs may work within one of the increasing number of research software engineering teams that have been set up at universities and research organisations over the past decade, or they may be embedded within a research team. They may have a job title that officially recognises them as an RSE, or they may have a standard research or technical job title such as Research Assistant, Research Fellow, or Software Engineer. Regardless of their job title, RSEs share a set of core skills that are required to write software, understand the research environment, and ensure that they produce sustainable, maintainable code that supports reproducible research outputs, following the FAIR principles [3].

This paper defines a set of core values and competencies, agnostic of specific technical capabilities or research domains, which an RSE should acquire during training and formal education. By defining these competencies, we provide a guiding framework to facilitate the training and continuous professional development of RSEs, thus helping to provide a positive impact on research outputs and, ultimately, society as a whole. These competencies draw upon skills from traditional software engineering practice, established research culture, and the commitment to being part of a team. While there is anecdotal evidence that academic software engineering practitioners would have chosen different competencies, we will argue that this trifecta of skills is exactly what is needed for modern digital research.

While this paper is based on workshop discussions that were attended largely by Research Software Engineers (deRSE23 in Paderborn, un-deRSE23 in Jena, Germany), we believe that the competencies formulated here can offer far-reaching impact beyond the domain of RSE into adjacent fields of science and, indeed, the wider research community, since most research involves some amount of data management, processing and visualisation. At the same time, funding bodies and computing infrastructure providers prioritise projects that generate archived, annotated, re-usable, and potentially remotely executable data. In particular, funding agencies and research managers will find the discussion in this paper valuable in order to discover where RSEs see their place in the existing landscape of scientific domains and how to support the work of RSEs at different positions and career levels.

The outline of the paper is as follows. We start with a non-exhaustive overview of existing initiatives in Section 2. Section 3 elaborates on the values that provide the guiding principles for the work of an RSE. Section 4 defines a set of core skills based on these values. The skills themselves fall into three categories, namely “software engineering”, “research”, and “communication” skills, reflecting the hybrid nature of an RSE. To justify the selection of these skills, we also list some current tasks and discuss the skills used therein. As with any general skill set, not all RSEs will need to use all the skills highlighted to the same level of expertise. Therefore, Section 5 examines how much a person needs to know depending on their education or career level or on the type of projects they would like to be involved with. In the same section, we provide an overview of what skills and limitations an RSE in different team structures typically has, and we give recommendations for organisations that need to support RSEs. Section 6 provides a list of RSE specialisations and discusses the level of skill needed to work in each of them, before we conclude the paper with details of future work in Section 7 and conclusions in Section 8. Finally, Appendix A provides an example curriculum in Appendix A.1, a story like description of a fictional RSE career progression in Appendix A.2, and a list of existing skills and certifications in related fields, in Appendix A.3.

## 1.1 Terminology

Depending on the national research environments and processes that readers are familiar with, the notion of the terms *software* and *research* might differ. Therefore, to avoid ambiguities, we define these as follows:

**Software:** Source code, documentation, tests, executables and all other artefacts that are created by humans

during the development process that are necessary to understand its purpose.

**Research software:** Foundational algorithms, the software itself, as well as scripts and computational workflows that were created during the research process or for a research purpose, across all domains of research. This definition is broader than in Barker et al. [3] and is the outcome of a recent discussion in Gruenpeter et al. [25].

**Research software engineers:** People who create or improve research software and/or the structures that the software interacts with in the computational ecosystem of a research domain. They are highly skilled team members who may also choose to conduct their own research as part of their role. However, we also recognise that many RSEs have chosen specifically to focus on a technical role as an alternative to a traditional research role because they enjoy and wish to focus on the development of research software.

## 2 Related work

Various initiatives are working to support technical professionals develop their computational skills. Particularly related to this work are initiatives that aim to define sets of such skills and guide the community with certification programs and training resources.

**RSE Competencies Toolkit** The RSE Competencies Toolkit [48] is a community project that developed out of a hack day activity at the 2023 edition of the annual Software Sustainability Institute Collaborations Workshop [8]. The toolkit provides a web application that aims to support technical professionals in understanding how to develop their skills. It enables them to build a profile of their competencies within the system, while it also provides a set of training resources that are linked to a competency framework.

**HPC Certification Forum** The HPC Certification Forum [58] is working towards providing a certification process for High Performance Computing skills. As part of this process, the group is developing a Competence Standard [57] and an associated skill tree that provides a classification of HPC competencies. This work aims to develop a standardised representation of relevant HPC knowledge and skills which can, in turn, lead to structured and recognised sets of skills that can underpin the certification process.

**EMBL/EBI Competency Hub** The EMBL/EBI Competency Hub [11] provides a bioinformatics/computational biology-focused example of a competency portal. In addition to collecting information on a range of competencies that can be browsed within the web-based tool, it also provides career profiles for roles within the domains that EMBL/EBI focuses on. The hub provides access to variety of training resources that are linked to the specific competencies that they relate to. This enables learners to more easily find the right training materials in order to support their career development journey, helping them to identify what they might want to learn and in what order.

**Training-focused initiatives** Further initiatives implicitly define sets of competencies by providing (open) teaching material for selected skills. This is a non-exhaustive list of related initiatives, which will be discussed in more detail in a separate publication. In some cases, the activities extend beyond training, but they do not focus on defining frameworks of competencies.

One prominent example is the Carpentries [56], a non-profit entity that supports a range of open source training materials and international communities of volunteer instructors and helpers who run courses around these materials. A similar framework is provided by CodeRefinery [7], currently funded by the Nordic e-Infrastructure, as well as SURESOFT [55, 4], a DFG funded project at TU Braunschweig and FAU Erlangen-Nürnberg, targeting more advanced software engineering topics like Software Design Principles, Design Patterns, Refactoring, Continuous Integration and Test Driven Development.

There are also several initiatives focused on training HPC-oriented RSEs, such as the Partnership for Advanced Computing in Europe (PRACE) [44] (with material aggregated on various websites, e.g. on EuroCC Training [13]), UNIVERSE-HPC (Understanding and Nurturing an Integrated Vision for Education in RSE and HPC) [61] (a project funded under the UK's ExCALIBUR research programme [16]), and the EuroCC National Competence Center Sweden (ENCCS) [14], which offers a collection of lessons for HPC skills [12].

Initiatives focused on Germany include EduTrain [42] (a section of NFDI [21]), the Helmholtz Federated IT Services platform (HIFIS) [26], and the already mentioned SURESOFT [55].

## 3 Values

The activities of an RSE are guided by ethical values. In addition to the values for good scientific practice [18], RSEs also adhere to the software engineering Code of Ethics [23]. Central to that code is the RSE's obligation to commit to the health, safety and welfare of the public and act in the interest of society, their employer and their clients. Further values loosely based on that code include the obligations

- to commit to objectivity and fact-based, honest research conclusions,
- to promote openness and accountability in the research process,
- to take great care to develop software that adheres to current best practices,
- to judge independently and maintain professional integrity,
- to treat colleagues and collaborators with respect and work towards a fair and inclusive environment, and
- to promote these values whenever possible and make sure that they are passed on to new practitioners.

RSEs often assume a multifaceted role at the junction of research, software engineering and data management. They work with a varying and diverse set of colleagues that might include other developers, support unit staff and academics of different fields and all career stages. This situation yields a specific set of challenges RSEs should be aware of to consciously make ethically sound judgement calls. We list some example areas that highlight present-day challenges.

### 3.1 Current challenges

#### 3.1.1 Handling of data and personal data

A lot of RSE work involves the manipulation or creation of data processing devices. We highlight that professional conduct requires these creations to be reliable and to maintain data integrity. In particular, the way that personal data is handled can have far-reaching implications for society. Independent of the encoding into the respective national law in an RSE's jurisdiction, the right to information privacy is internationally recognised as a fundamental human right, e.g. in the European Convention on Human Rights [9, 29]. RSEs need to be aware of this topic's importance and deal with tensions that might arise with researchers' desire for trouble-free sharing of data, thereby expecting openness about the research process, versus the integrity expectations of the society towards IT systems. Handling personal data also has ramifications for information security considerations during the software development process. Data protection is a difficult subject, so RSEs should notice when they need to consult external expertise, for example when dealing with special topics such as cryptography or re-identification attacks [27].

#### 3.1.2 Mentoring and diversity

RSEs are often experienced professionals who instruct and work closely with early career researchers. Similarly to academic supervisors, they bear a certain responsibility to guide and advise younger colleagues with respect to career development and the achievement of academic goals. According to the UNESCO Science Report [50] women account for 33.3% of all researchers while the majority of researchers come from G20 countries (88.8%). This imbalance is even more pronounced in software engineering with a majority of developers identifying as white male [54]. Thereby, to promote their values of an honest, open, and inclusive research space, they should be aware of the diversity problem and help to mediate it whenever they have the chance to do so.

#### 3.1.3 Shaping digital science

Through writing research software, RSEs have a pivotal position in the process of scientific production. Their choices might determine whether the respective research is reproducible or not, whether the results can be re-used, whether future research can build on existing tools or has to start from scratch. Builders of larger research-infrastructure projects determine to some extent the possibilities and limitations of future research and therefore need to be able to make a value-based judgement on topics such as open science, path dependence, and vendor lock-in.

#### 3.1.4 Emerging challenges

RSEs often operate at the cutting edge of technological development and therefore might have to deal with technologies of which the dangers and drawbacks are still poorly understood. A current example is the rush for the application of large language models (LLMs), where RSEs working in these fields should stay up-to-date and

be able to help researchers assess topics such as training-data bias, LLM “hallucinations” or malicious use, with the greater goal of making these powerful tools work for the welfare of society.

## 4 Required generic RSE skills

The role of an RSE lies somewhere on the spectrum between that of a researcher (the “R”) and a software engineer (the “SE”) and, therefore, requires competencies in both fields. RSEs typically apply their knowledge and experience in larger teams which allows them to cultivate this hybrid nature. Therefore, we categorise the competencies into three categories: *software engineering skills*, *research skills*, and *communication skills*, with a particular focus on the software and research cycle and the scientific process. The generic skills are relevant in a broad setting and form the foundation for specific specialisations. These competencies have been chosen in order to make RSEs contribute to an open and inclusive research environment, with tools that respect their professional values.

These skills and competencies come into play in various forms: The RSEs themselves need to acquire and develop them as their career progresses (**Career level**). However, some knowledge of software and data processing is required at all academic levels and for all positions (**Academic Progression**). The relative importance of the skills and competencies also depends on the size of the RSE team (**Project team size**). Finally, different sets of skills are emphasised in the different RSE specialisations (**RSE specialisations**).

### 4.1 Software engineering skills

There are many software engineering curricula out there, that try to define which tasks a software engineer should be able to perform. A recent example highlighting some aspects in more detail than here is Landwehr et al. [36]. The software skills outlined here are required to make research software adhere to the FAIR principles, which are aspects of good scientific practice. Chue Hong [6] defines different levels of research software reusability and the extent to which the software engineering skills need to be applied to reach them.

#### 4.1.1 Creating documented code building blocks (DOCBB)

The RSE should be able to create building blocks from source code that are reusable. This ranges from simple libraries of functions up to complex architectures consisting of multiple software packages. An important part of reusability is that at least oneself, and ideally others, are able to understand what a piece of software aims to do and how to enable others to use the provided functionality. This is primarily achieved through a “clean” implementation and enhanced by documentation. Documentation ranges from commenting code blocks to using documentation (building) tools.

#### 4.1.2 Building distributable libraries (LIBS)

The RSE should be able to distribute their code on their domain/language specific distribution platforms. This almost always encompasses handling/documenting dependencies with other packages/libraries. It sometimes requires knowledge of using build systems to enable interoperability with other systems.

#### 4.1.3 Adapting to the software life-cycle (SWLC)

The traditional software life-cycle defines the stages that form the process of building a piece of software. Initial development generally involves a creative process where requirements are gathered and analysed, followed by a formulation of a plan to fulfil them that is finally implemented. This is then followed by testing that things work as expected and that they continue to do so into the future. Often the development is iterated. We emphasise that the life-cycle is not complete here but also includes periods of maintaining a software and also withdrawing software from its original use. The RSE should be aware of this life-cycle and be able to predict and cater to the changing needs of software as it moves through the stages.

#### 4.1.4 Use repositories (SWREPOS)

The RSE should be able to identify and use fitting public platforms (so-called software repositories or repos) to share the artefacts they have created and invite the public to scrutinise them for public review.



#### **4.1.5 Software behaviour awareness and analysis (MOD)**

We define this as a certain quality of analytical thinking that enables an RSE to form a mental model of a piece of software in a specific environment. Using that, an RSE should be able to make predictions about a software's behaviour. This is a required skill for common tasks like debugging, profiling, optimising, designing good tests, or predicting user interaction. An important facet of this capability relates to information security. RSEs need to consider the safety and integrity of personal data and other sensitive information and make sure that they do not negatively impact the integrity of their institution's network.

### **4.2 Research skills**

#### **4.2.1 Curiosity (NEW)**

RSEs gain their reputation from their effectiveness in interacting with their domain peers. Therefore, some curiosity together with a broad overview of the research field is required as this enables the RSE to learn new methods and algorithms directly from domain peers. Curiosity is also reflected when an RSE is actively trying out new tools. Lifelong learning is then no longer just a phrase but becomes a motivation to work.

#### **4.2.2 Understanding the research cycle (RC)**

One of the crucial skills of RSEs is their mental proximity to research. They embrace being part of a larger community which, despite friendly competition, shares the common goal of gaining knowledge for its own sake and not just for personal or commercial gain. Thereby they know that they are part of a bigger cycle that involves many other parties in and outside their domain, and also that their software can be utilised at different stages of the research cycle by different people. Like other researchers, RSEs are open to discussions and arguments beyond their own expertise and appreciate the underlying principles of good research, like publications, reviews and reproducibility.

#### **4.2.3 Software re-use (SRU)**

One goal of FAIR software is to avoid unnecessary duplication of work by reusing existing work instead. To (re-) use software, researchers have to be able to find it and then easily evaluate if the software actually suits their needs. Apart from functionality, the integration with other software, expected sustainability, and extensibility also have to be part of this evaluation.

#### **4.2.4 Software publication (SP)**

The second part of FAIR software is concerned with publishing new and derived works and making them available for re-use by the research community and the general public. RSEs need to have a basic understanding of common software licence types, such as "proprietary", "copyleft", and "permissive", the compatibility of different common licences and the ramifications for re-using and composing programs. Finally, RSEs will need to properly execute the technicalities of software publishing, such as applying licences, honouring copyright statements and crediting contributors.

#### **4.2.5 Using domain repositories/directories (DOMREP)**

Almost all research software is developed within a specific scientific domain. Some software may be able to cross boundaries, but the majority will have a home domain, with which it needs to be able to interact. The RSE needs to be aware of any domain specific software repositories, data sets and catalogues. The RSE also needs to be aware of how their software can interact with the existing domain-specific data repositories.

### **4.3 Communication skills**

RSEs do not work in isolation. They are embedded in a research group or work within a team of RSEs supporting particular research projects. RSEs often need to interact with and facilitate communication among colleagues, clients and contractors with a very broad spectrum of background-knowledge, specialisation, expectations, and experience. Communication skills are therefore crucially important. Team skills are also mentioned in common guides for software engineering such as the software engineering body of knowledge [5]. However, the interpersonal and organisational skills and the capacity for adaption required to work in a research setting warrants a much stronger emphasis on this field of competence.

#### 4.3.1 Working in a team (TEAM)

Working in a team is all about communication and teamwork. For example, RSEs need to be able to explain particular implementation choices made and may even need to defend them. Within a team of RSEs code reviews improve knowledge transfer and increase team cohesion. The team might change on a project-to-project basis and might be comprised of colleagues with very different backgrounds including, for example, IT staff, domain scientists and technicians working alongside software engineers. The shared values come into play and each RSE needs to ensure that these values are lived by and passed on to others. Senior RSEs may lead a team of RSEs.

#### 4.3.2 Teaching (TEACH)

RSEs have many opportunities to teach. These range from inducting new colleagues to teaching digital skills either through short courses, for example from The Carpentries [56], or entire lecture series. RSEs may also act as mentors and consultants. Code review also includes aspects of the teaching skill.

#### 4.3.3 Project management (PM)

The RSE should have knowledge about project management. At some institutes, it follows the practices of the local research groups, but it is useful if an RSE knows its place in a PM scheme, or can bring in new ideas for improvement. Project management in research software engineering poses specific challenges (see **USERS**) that might require the capacity to flexibly adapt to changing conditions and deviate from common project management methods.

#### 4.3.4 Interaction with users and other stakeholders (USERS)

Since research software is often developed as part of the research process itself, its requirements and specifications might change with the progression of research. Stakeholders of research software often change across different research projects or even within the course of one project. Roles in connection with research software are often in flux and diffuse. For example, a single person might be user, developer and project manager at the same time. Often this means it is necessary for an RSE to think “outside their comfort zone”, but at the same time to be able to convey their knowledge and experience to experts of other fields or persons at different hierarchy levels in a way they can understand more easily. These conditions pose specific challenges for requirements analysis, project management, training and support.

### 4.4 RSE tasks and responsibilities

These skills, while already numerous are also generic on purpose. They span a multidimensional space in which the day-to-day tasks and responsibilities of an RSE can be found. A snapshot of what this means today was obtained from learners and novice RSEs that we asked during the Paderborn workshop what they would like to have learnt. Among the top five things mentioned were:

- **Testing.** This task is a manifestation of the SE competencies of DOCBB and MOD since a model of the software is required in order to write good tests that facilitate understanding and documentation. Today this encompasses the knowledge of testing frameworks and CI/CD practices.
- **Contributing to large projects.** This is a topic that requires competency in SWREPOS, SRU, SP in order to understand the ramifications of sharing, and DOCBB, since the contributed code has to be understood by others. Interacting with project members depends on the TEAM skill. Today this entails the effective use of collaborative platforms like GitHub/GitLab, honouring a project’s code of conduct, and some knowledge of popular software licences like e.g. the GPL.
- **When or why to keep repositories private.** This decision requires knowledge in the RC, to understand when it makes sense to open up or close down a repository. The USERS, TEAM and sometimes SP skills are required to make this decision. Furthermore, knowledge of the practices and contractual regulations of the RSE’s institution are also required.
- **Proper development.** This broad topic requires all the SE skills. Of course, these are the competencies that are the most fluid since they have to adapt at a high rate to technological advancements. Additionally, proper SE skills often require knowledge of TEAM, and PM. Today this means effective use of IDEs, static analysis tools, design patterns, documentation (for oneself and others), etc.
- **Finding a community.** This can be interpreted in two different ways. First, we have the aspect of community building for a research project. Since this deals with software that is supposed to be used in research



this requires knowledge of RC, USERS, and also NEW, in order to effectively interact with domain scientists. Today, an example is a presence on social media. The other TEAM-related aspect is the embedding of RSE graduates into the community of RSEs, sharing the same set of values and competencies. We envision our RSE graduates to be a part of a strong network of other RSEs, tool-related communities, and the classical domain communities, making them more effective at supporting research. These networks are a lifelong manifestation where RSEs work to provide an inclusive environment for their peers and provide opportunities for life-long learning.

Beyond that, we feel that today other important tasks of RSEs are

- Mentoring colleagues. This necessitates giving good advice that fits to a projects stage in its life-cycle, thereby requiring knowledge of (SWLC), and its context in its research domain and thus (RC). Research software often starts out as a tool to answer a personal research question and becomes more important when other researchers rely on it. Some research software might even be used to deal with critical questions such as weather forecasting or medical diagnosis. To formalise the process of giving good advice a classification of software is commonly used [62, 49] where research software can move from one class to another during its life-cycle. Schlauch, Meinel, and Haupt [49] classify applications based on their scope and criticality and provide software engineering recommendations. The RSE needs to be able to identify the application class they are dealing with and apply the respective RSE practices.
- Enforcing reproducibility. Projects like ReproHack [46] can greatly help in fostering that competency.

## 5 How much do different people need to know?

Now that we have the different competencies, we can explore various dimensions of these competencies, depending on their circumstances. A strong beneficiary of specialised RSEs can also be newly formed RSE centres at research institutions.

### 5.1 Career level

At different career levels, differing skills are required. We have set this up according to the following separation often applied within a single project:

- Junior RSE: These are people who are in the earlier stages of their RSE career journey, but they should still have the skills to contribute reliable and well-structured code to software projects.
- Senior RSE: They have gained experience and can set the standards in a software project.
- Principal RSE: Their actual job description varies a lot. These may be RSE team leaders based in a professional services type role, or they may be professors or research group leaders based in a more academic-focused role. They are often the people responsible for bringing in the funding that supports new projects and sustains existing projects. Generally speaking, they do not need to be actively involved in the day-to-day technical tasks, but they should be able to guide projects from both a technical and a research perspective while providing an inclusive working space.

Table 1, Table 2, and Table 3 elaborate on the required facets of the competencies in different roles. A story-like example of an individual through the hierarchies can be found in Appendix A.2 .

Table 1: Levels of software eng. skills expected per RSE career stage.

Competency	Junior RSE	Senior RSE	Principal RSE
DOCBB	Should be able to write reusable building blocks.	Same as junior, but the quality should set the standard for the project, while following current best practices.	Should know the current best practices and point their staff to the right resources.
LIBS	Should be able to use package distribution platforms.	Same as junior, but should also be familiar with current best practices for building and deploying packages.	Should ensure that their project is available via an up-to-date and secure distribution platform.
SWLC	Should be aware of the software life-cycle.	Should know where in the life-cycle their project is and which decisions are likely to lead to technical debt.	Should know how to manage and steer development/project resources accordingly. Should also have an understanding of the potential consequences of key project management decisions.
SWREPOS	Should seamlessly interact with the repository of their project.	Should be well-versed in the intricacies of a repository, and probably interact with repositories of multiple projects.	Should promote the use of repositories and be able to convey best practices to junior and senior RSEs.
MOD	Should have a basic grasp of their piece of the software in order to use basic tools such as a debugger.	Should understand the characteristics of large parts of the codebase considering a variety of the metrics.	Should understand the big idea of the software project in order to define the task that the software solves.

Table 2: Levels of research skills expected per RSE career stage.

Competency	Junior RSE	Senior RSE	Principal RSE
NEW	Should have some curiosity to fit into research teams.	Same as junior, but a curiosity to enhance the code base is required.	Should have curiosity to know in which direction to steer the project.
RC	Should be aware of the research life-cycle.	Should know the position of the project in the research life-cycle.	Should know what is necessary for the project to fit into its position in the research life-cycle.
SRU	Should be aware of software reusability tools.	Should be able to search with software reusability tools.	Should be able to effectively search with SRU tools and to evaluate and perform the integration of a library into the project.
SP	Should be aware that software publication needs to consider issues of intellectual property.	Should be able to correctly publish software in simple cases and to identify cases where professional legal advice is needed.	Same as senior, plus the ability to take the future publication of software into account when initiating and guiding larger software collaboration projects.
DOMREP	The RSE should be able to interact with the domain repository.	Same as junior RSE.	Same as junior, and should know about how it fits into workflows surrounding these domain repositories.

Table 3: Levels of communication skills expected per RSE career stage.

Competency	Junior RSE	Senior RSE	Principal RSE
TEAM	Should be able to work in the team in order to effectively fulfil the given tasks. Should be able to learn from code review.	Should be able to break down tasks into more easily digestible sub-tasks.	Should be able to lead the team and set the respective direction.
TEACH	Should be able to perform simple peer-to-peer on-boarding tasks.	Should be able to explain logical components and the general architecture to other RSEs.	Should be able to effectively communicate about all high-level parts of the project.
PM	Should be aware of the employed project management method.	Should be able to use and adapt the employed PM method.	Should be able to design and adapt the employed PM method.
USERS	Should be able to communicate with non-SE users of the project.	Same as junior RSE, and be able to interpret the feedback.	Same as senior, and should also be able to effectively take feedback into account when steering the project.

## 5.2 Helpful RSE skills for researchers in an academic career

In the previous section, we looked at the competency levels needed for RSE specialists. However, many of these competencies are important for researchers in academia as well. Naturally, the ‘R’ competencies apply and research in general is increasingly team based. Additionally, many researchers in fields from classical examples like numerical mathematics or theoretical physics to newer disciplines like digital humanities will spend time in their research on writing and developing software. Therefore, RSE focused training, e.g. in a master’s programme, is also beneficial for students in these fields resulting in a broader audience.

This section outlines how the RSE competencies could be reflected at all academic levels. It is important to note that this section does not reflect the current state of academic training and research institutions. Instead, it summarises the discussions with and between workshop participants at different levels of academic progression on what they would have liked to learn at an earlier stage or know before starting their current position. While individuals already work at implementing some of these changes and teaching these skills, it has not yet reached a systemic level.

The text is organised along the academic progression path (bachelor’s degree, master’s degree, PhD, Postdoc, PI/Professor). Since each level is based on the previous levels, we presume that the skills and competencies at each level also encompass those of the previous levels. Due to the broad need throughout academic specialisations, the described levels serve as a baseline and certain fields will require higher SE skill levels as development is a large part of their actual research.

**Bachelor’s level** Students at the undergraduate level mostly consume science/knowledge. During their studies, they should also learn about the existence of digital tools and structures. Undergrad students should be aware that RSEs exist and that software has different quality aspects (DOCBB). They should be aware of domain specific tools (LIBS, SRU) and where to find them (SWREPOS, DOMREP). At this level, it is sufficient to consider software as black boxes (USERS) although some training in data presentation would be very helpful and a good way to find out about programming (MOD, NEW). They should have an awareness of software licences and whom to ask regarding licensing issues (SP). They will be taught about the research cycle (RC) and that researchers often work in groups (TEAM). During practicals, they will have an opportunity for peer learning (TEACH).

**Master’s level** A student at a master’s level can participate in science and should therefore be able to use “some” digital structures. A master’s student needs to be aware of relevant tools and data sets for their domain, where to find them and how to use them (LIBS, SWREPOS, DOMREP). They should be able to process and present their data (MOD). They need to understand how their research depends on software (SWLC). Working on their master’s thesis allows them to understand the research cycle (RC), practice project management (PM) and collaborate with other members of their research group (TEAM).

**PhD** A PhD student performs independent research under guidance. They need to know relevant tools and structures. They should know where to find information about tools and where to find help using them (DOCBB, SWREPOS). They should be able to use the tools (LIBS) and identify and report bugs (MOD). They need to be aware that the user’s perspective is different from the developer’s perspective in order to be able to write bug reports (USERS). They might produce new software (MOD, SRU), in which case they need to understand how to licence their code for publication (SP). PhD students need to be curious to be able to conduct their research. In order to be able to explore new tools (NEW) they must be able to evaluate research software (SWLC). They need to be able to interact with services (RC) and domain specific repositories (DOMREP). They should be able to supervise a student (TEACH).

**Postdoc** Postdocs are independent researchers. Their role is similar to that of a PhD student, with a deepened focus on their research career. However, they are proficient users of all relevant tools, which makes them active contributors to their domain of research. They need to be aware of more advanced topics regarding intellectual property rights, such as patents (SP).

**PI/Professor** They are experts in their field and should be able to give proper guidance to their students on which digital tools are currently relevant. They should be aware of the skills of an RSE and when they might need one in their group. They should encourage their students to use relevant tools (LIBS). They need to be able to judge the suitability of the software (SWLC) and follow the interactions between relevant projects (SWREPOS). They should be able to advise their students on the legal aspects of software production and distribution (SP). They should be able to contribute meaningfully to the steering decisions of the software in their field (USERS).

They need to guide students and give full-size lectures (TEACH). They need to manage and lead their research group (PM, TEAM).

### 5.3 Project team structures

In Table 4, Table 5, and Table 6, we look at individual or team competencies and approaches to them, considering how these differ depending on whether an RSE or researcher is working alone on a software project, or whether they are working as part of a team of research software developers. We extend this to consider how things differ when a developer or a group of developers is based locally within a research team or department, or when they are based in a dedicated, centralised RSE team. We also look at organisational aspects in the context of each of the considered competencies, since there are a variety of ways that organisations can contribute to and support them, complementing those proposed by Katerbow and Feulner [33]. Some of them are brought to life in the example career path of Appendix A.1. We first summarise the meaning of each of the columns in the tables:

- **Competency:** The code assigned to the competency being considered, as defined in Section 4.
- **Individual developer (Locally-based):** A single person working on some research software - often a researcher with RSE skills. Often time-constrained, may be self-taught.
- **Individual developer (RSE team-based):** A single person working on research software - generally a professional RSE assigned to support another team's software on their own, who however is connected to an RSE team.
- **Group of developers (Locally-based):** A group of RSEs/researchers within a research group or team, working together on developing software to support or undertake a single research goal/project. Similarly to the individual RSE, they are often researchers with RSE skills, often self-taught.
- **Group of developers (RSE team-based):** A group of members of the RSE team working together on a research software project for a research group.
- **Organisation-level support:** How the defined competencies are recognised and represented at an organisational level and what the organisation can do to support the RSEs in the context of the different team structures. These can be read as policy/action recommendations.

These tables take the perspective of the expected skill set of each developer or team of developers, similarly to personas in a user experience analysis. The current situation may differ.

Table 4: Levels of software eng. skills expected per team structure.

Competency	Working as an individual developer		Working with a group of developers		Organisation-level support
	Locally-based	RSE-Team based	Locally-based	RSE-Team based	
DOCBB	Focuses on getting outputs to support research. Is not very familiar with code quality and structure. Follows basic best practice guides.	Puts greater focus on reusability, documentation, and knowledge of best practices, but potentially lacks domain knowledge.	Has more opportunities to discuss and share ideas, but team members may be less aware of key practices.	Has stronger ingrained focus on team-based PM and development methodologies, resulting in higher quality, more reusable code.	Should offer training and other resources in core topics to support individual developers. Should have research software guidance/policies that provide advice.
LIBS	Does not emphasise code reusability and sharing/distribution.	Puts greater focus on reusability/sharing, but likely not as part of the project aims.	May want to develop reusable shareable outputs for a specific case. Needs clear guidelines.	Focuses on quality and best practices. Reusability/packaging driven by project needs and spec.	Should provide policies on reusability/sharing. May be driven by requirements/policies of the funding agency.
SWLC	Manages the complete life-cycle, bus factor equal to 1.	The team supports parts of the software life-cycle, but with low bus factor.	The team infrastructure and tooling supports the life-cycle and sustainability.	The bus factor may still be low in parts of the code. Need to think about coherent life-cycle management across the team - generally a key area of expertise for an RSE team.	Should support with training. Organisation may also provide site licences for, e.g. management tools.
SWREPOS	Uses repositories for code management and demonstrating outputs, e.g. for supporting academic credit, but may be missing skills.	As locally-based, but professional RSEs are generally very experienced with use of repositories and their many features.	Uses repositories to collaborate inside the team. Can benefit from short courses on effective use.	Uses repositories extensively for project management, issue tracking, etc. in addition to code itself. May train others.	Should offer enterprise repository set ups, site licences etc. Also fund either internal or external training for this vital research software development tooling.
MOD	Needs full awareness of entire codebase to extend/maintain. If project taken on from another developer, there may be challenges in transferring the mental model.	As local, but more aware of need for future transition to other developer(s), likely provides docs, issues, and other support from central services to support this. May only need to know parts of the code.	Internal team training ensures ability to build necessary mental model of codebase and to document it via text or tools for sustainability.	As local team, but likely more aware of tooling and practices in place within RSE team. Distributing work makes it only necessary for each developer to understand code related to their assigned tasks.	Should provide training and retain experience via coordinating and provide support for mentoring/community activities. Establishing RSE departments with specialists for certain aspects of software will improve overall turnaround times.



Table 5: Levels of research skills expected per team structure.

Competency	Working as an individual developer		Working with a group of developers		Organisation-level support
	Locally-based	RSE-Team based	Locally-based	RSE-Team based	
NEW	Struggles to learn new methods and skills due to split curiosity between research goal and software project.	Gets support from the RSE team to explore new methods and skills, make relevant contacts and learn more about the domain.	Has increased interest in learning new methods and skills, but still prioritises domain research.	As per Individual (RSE team).	Should reach out to relevant local groups to facilitate training and sharing of know-how on new technical processes and tooling.
RC	Is familiar with the research life-cycle in their domain, especially when embedded in a research team.	Is familiar with the RC, although they may not have domain knowledge, which a group can provide.	Is familiar with the RC and can share knowledge within the team.	One or more members of the team are strongly aware of the RC.	Should provide extensive infrastructure to manage the research life-cycle, supporting researchers/RSEs.
SRU	Has limited awareness of existing solutions and limited support in this regard.	Is familiar with software sharing and can discover tools and platforms.	As per individual (local), but being part of a team can help to address this.	As per individual (RSE Team).	Should run local environments to host software, catalogue software, and/or provide institution-level access to platforms that support this.
SP	Has limited knowledge and motivation regarding software publication.	Applies practices, workflows, and policies established in the RSE team.	As per individual (local) developer.	As per individual (RSE Team).	Should raise awareness about software as a publishable scientific output, provide recommendations and checklists to support software publications, and have legal experts in place to offer advice on complex cases.
DOMREP	Domain researchers working on software are likely to be more familiar with the domain-specific solutions.	RSEs may need guidance from domain researchers around domain-specific repositories if they have a background in a different domain.	As per individual (local).	As per individual (RSE Team).	Should host domain-specific repositories for areas that the organisation works extensively in, but this is likely to be handled at a research group level.

Table 6: Levels of communication skills expected per team structure.

Competency	Working as an individual developer		Working with a group of developers		Organisation-level support
	Locally-based	RSE-Team based	Locally-based	RSE-Team based	
USERS	May have additional skills to safeguard potential future development and maintenance of the software for external users. Resourcing for future maintenance may be a challenge.	Has additional skills or can access support to safeguard potential future development and maintenance of the software for external users.	Needs to safeguard future development and maintenance of the software for external users, but may not have the skills or resources to support this.	Applies best practices to prepare the code for external users, while the team provides infrastructure and/or specialised RSEs for user support.	Should have institutions that are able to offer support with outreach and publicising outputs.
TEACH	May be independently involved in training activities.	May be able to support researchers with core technical skills.	Shares knowledge and skills within the group (peer support).	Supports teaching more widely, either through organised courses or ad hoc activities such as “code clinics”.	Should have programs for a diverse range of teaching/training activities, such as an RSE curriculum, as described in <a href="#">subsection A.1</a> .
PM	Is organised enough to be able to transfer the code-base to future developers.	Follows the project management approach set by the team, or can suggest such PM approaches.	Has additional PM challenges, but may not have awareness of or experience with key PM skills, which can acquire with low-key courses.	Team provides well-structured approaches and tooling to support management of projects.	Should offer training to support management of projects. May offer organisation-level tooling.
TEAM	N/A	Must be able to work effectively with their home RSE team, as well as with researchers they are potentially developing code for.	Must have strong team skills and knowledge to support team-based software development.	Must be able to work and collaborate effectively in an interdisciplinary team, use required tools and processes, infrastructure, etc.	Should offer support with team work and promote interdisciplinary interaction. Should facilitate team-building initiatives, also on a social level.

In the table above, we have looked at how different competencies can be related to and handled by researchers and RSEs working in different environments within an organisation and how the organisations themselves can contribute. We recognise that this is a challenging area to gain a detailed view of and that our content in the table is still a significant generalisation. We talk about the “research software engineer” as a single entity but as the field expands, we expect to see more roles and job titles emerging around the RSE concept, many of which fit under the wider umbrella of research technology professionals (RTPs). Examples are different RSE-like computational roles of the European Bioinformatics Institute (EMBL-EBI)’s BioExcel competency framework [45] (also Appendix A.3.2), as is a range of different roles from King’s Digital Lab at King’s College London [47].

## 6 RSE specialisations

What we have defined above are intended to be base skills that an RSE irrespective of domain, place, and time should know about. But not all RSEs are created equal, they specialise in different areas, some of which we want to present below. Many of the specialisations may overlap, so the same RSE might for example work on data management and open science. We categorise them into those that can be viewed as a specialisation within RSE-specific topics, while other RSEs might expand their skill set and profession to areas, that are not typical for an RSE.

### 6.1 Specialisations within the core RSE competencies

**OpenScience RSE** Open science and FAIRness of data and software are increasingly important topics in research, as exemplified by the demand of an increasing amount of research funding agencies requiring openness. Hence, an open science RSE is required to have a deeper knowledge in (RC) and how to distribute software publicly (SRU, SP). Open Science RSEs can help researchers navigate the technical questions that come up when practising Open Science, such as “How do I make my code presentable?”, “What do I need to do to make my software FAIR?”, or “How do I sustainably work with an (international) team on a large code base?”. Like the Data-focused RSE, they have a deep understanding of research data management (RDM) topics.

**Project/community manager RSEs** When research software projects become larger, they need someone who manages processes and people. This gap can be filled by people who invest in the (PM), (USERS), and (TEAM) skills, as exemplified in Appendix A.2. Building a community around a research project is an important building block in building sustainable software [52], so these RSEs play an important role, even if they do not necessarily touch much of the code themselves.

**Teaching RSEs** RSEs interested in developing their (TEACH) skill can focus on teaching the next generation of researchers and/or RSEs and will play a vital role in improving the quality of research software. They need to have a good understanding of all RSE competencies relevant to their domain and additionally should have experience or training in the educational field.

**User interface/user experience designers for research software** Scientific software is a complex product that often needs to be refined in order to be usable even by other scientists. To facilitate this, there are people required that specialise in the (DOCBB) and probably the (LIBS) competency with a focus on making end-user facing software really reusable and hence FAIR. This task is supported by strong (MOD) skills to reason about the behaviour of potential users of the software.

### 6.2 Specialisations outside the core RSE competencies

**\$(DOMAIN)-RSE** While software is the lingua franca of all RSEs, there will be RSEs that have specialised in the intricacies of one particular research domain, such as medical RSEs, digital humanities RSEs, or physics RSEs. This can often serve as a base domain for RSE specialisation as in Appendix A.1

**Data-focused RSE** RSEs working at the flourishing intersection between data science and RSE. They are skilled in cleaning data and/or running data analyses and can help researchers in setting up their analysis pipeline and/or RDM solutions. When the field requires research on sensitive data or information, e.g. patient information in medicine, this RSE should have knowledge about secure transfer methods and/or ways to anonymise the data. As part of RDM, this RSE profile is able to support all stages of the research data life-cycle [43], with synchronous data management processes. Those processes implement established best practices for planning and documenting

of data acquisition in a data management plan (DMP), as well as for management, storage, and preservation of data, and publication and sharing of data in repositories according to the FAIR principles [66].

**Research infrastructure RSE** This RSE is interested in SysOps and system administration and sets up IT infrastructures for and with researchers. Therefore, this specialisation on the one hand requires a deep knowledge of physical computer and network hardware and on the other hand knowledge about setup and configuration of particular server software, like e.g. setup of virtual machines on hypervisors or the planning and setup of compute server clusters machine learning. As an interface between the researchers and the infrastructure, they take care of user management, access permissions, and configuration of required services.

**Maintenance RSEs** The constantly evolving software environment can hinder or prevent reproducibility. In this changing environment, a significant amount of effort in (research) software development needs to be spent on maintenance to ensure that software remains useful or even installable. With regard to which additional competency is required, these are people having experience with software stacks that are not part of the general curricula any more (e.g., COBOL or Fortran).

**High performance computing (HPC) - RSE** RSEs with a focus on High Performance Computing (HPC) have specialist knowledge about programming models that can be used to efficiently undertake large-scale computations on parallel computing clusters. They may have knowledge of (automatic) code optimisation tools and methods and will understand how to write code that is optimised for different types of computing platforms, leveraging various efficiency related features of the target hardware. They are familiar with HPC-specific package managers and can build dependencies from sources. They also understand the process of interacting with job scheduling systems that are often used on HPC clusters to manage the queuing and running of computational tasks. HPC-focused RSEs may be involved with managing HPC infrastructure at the hardware or software level (or both) and understand how to calculate the environmental impact of large-scale computations. Their knowledge of how to run HPC jobs and write successful HPC access proposals can be vitally important to researchers wanting to make use of HPC infrastructure.

**Machine learning (ML) - RSE** The development of research software based on machine learning (ML) requires specialised theoretical background and experienced handling of appropriate software in order to produce meaningful results. This involves knowledge about data analysis and feature engineering, metrics that are involved in ML, ML algorithm selection and cross validation, and knowledge in mathematical optimisation methods and statistics. ML-RSEs analyse and check the suitability of an algorithm if it fulfils the needs of a certain task and they play a main role in deciding and selecting machine learning libraries for a given task. The increasing usage of ML in numerous scientific areas with social impact involves an emphasised awareness and consideration of possible manipulative or discriminatory influences. At the intersection of data science [19] and Data-focused RSEs, the complex way of solving problems utilising machine learning calls for this separate specialisation.

**Web-development RSE** This RSE is skilled in web applications, front- and/or backend, and/or building and using APIs, for example for research data portals or big research projects. Ideally, this RSE should also have knowledge about (web) accessibility to allow a broad range of researchers or even the public to use the resulting applications. Therefore, a deep knowledge of web development skills is a required additional skill for this RSE.

**Legal-RSE** All RSEs are a go-to person for questions about licensing, in particular when mixing software components with different licences. But with the rising requirements from legislation, we foresee the need for RSEs that still have a background in RSE but extend it with a knowledge of legal processes, that cover corner cases and go beyond applying Best Practice guides. These requirements may arise in the area of publication of research software, as this also requires knowledge about particular laws or regulatory frameworks concerning data protection, like the GDPR within the EU [20]. Another area are legal aspects of cybersecurity and export control in science and research (see *Export Control in Science & Research* [17] for Germany). Legal-RSEs focus on facilitating the achievement of technically feasible solutions, while adhering to regulatory mandates. They are able to communicate and collaborate with lawyers.

## 7 Future work

Having the competencies is a first step to finding common ground around which to structure curricula, institutions, and teachers in this framework. Applications of them in an individual's career can be found in Ap-

pendix A.1. An omission that we found and that we would like to highlight in order to spark a community discussion is that RSEs that choose explicitly a science-supporting role outside of research will not be eligible for funding under the statutes of many funding organisations that require a PhD at minimum. To alleviate that and give RSEs in leadership positions a means to become eligible for funding themselves, since completion of scientific training is often a requirement [22], we propose the introduction of certificates that can be handed out by selected institutions. Examples of this could be doctorates based on software contributions to the scientific community, or new certificates like the certificate in Appendix A.2 that should become widely accepted. Beyond having that discussion, a diverse set of publications is already in the making. Next, we will work on how to institutionalise education. In that publication, we will detail how we organise our institutions and what qualifications our teachers need to have in order to effectively communicate our values. We will put forward ideas on how to build up bachelor's and master's programmes, of which a glimpse can already be found in this paper's appendix. We will show how we intend to provide the necessary continuous education for RSEs after graduation, and we will connect that with the integration of RSEs into a mesh of community networks aimed at supporting research, while providing them with an inclusive social network that further facilitates life-long learning. That publication will again intentionally be free of regional specifics, to also serve as a blueprint that other national RSE societies can build upon.

Another important building block is to provide people with online resources for use in their courses. This is the intention of the so-called "survey-publication". That survey of existing resources will not be carried out as a traditional publication, but it will be made available as a continuously-evolving online resource.

And finally, we will formulate the call to action - building on the previous publication on the necessary institutions, to lay down what is required to best support the continuous need for young RSEs to support digital science specifically in Germany.

## 8 Conclusion

This paper started from a community workshop at deRSE23 in Paderborn where people working in RSE related fields got together to figure out structures and ideas for educating newcomers to this field. One outcome of this diverse gathering is that RSEs from far away fields gather around similar core concepts, and at the same time share a vision of how to update the scientific ecosystem to the age of digitalisation. In this publication, we have tried to formalise these concepts. We have formulated a set of values that guide our actions in society, manifestly making RSEs part of the scientific community that shares the ideals of good scientific practice. At the same time, being software engineers, we cherish that we have to take responsibility for our tools. We continue with core competencies that have been intentionally formulated abstractly without referencing any particular information-processing device. As expected, we draw equally upon notions from software engineering and research, but find that we likewise require teamwork capabilities. We continue with detailing these competencies in various dimensions and find that a different amount is required in different positions and scientific domains, while proposing recommendations for organisations to foster the development of these competencies. Nevertheless, they are required and hence the values and competencies form a common denominator that unifies RSEs and enables them to identify with this domain that will become critically important for many areas of science. These competencies at the intersection of research and software engineering coupled with a firm belief in team processes makes RSEs sought after on the job market and their values make them responsible members of a digital society. This yields a qualification profile which makes an education based on it highly attractive to young people. At an institutional level, research performing organisations have a growing interest in fostering RSE training to support the use of FAIR data and FAIR software in the academic world, a direction determined by new incentives created by scientific journals and librarians. How we update existing institutions and set up new ones that provide this education will be the topic of a follow-up paper.

## Acknowledgements

FG thanks the GRF for funding through the SFB 1170 "Tocotronics" under the grant number Z03.

JC acknowledges support from the UK Engineering and Physical Sciences Research Council (UKRI-EPSRC) under grants EP/R025460/1 and EP/W035731/1.

JNG acknowledges funding from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Research Software Sustainability grant no. [391126171](#) (PI: Holm) and from the European Union – this work

has received funding from the European High Performance Computing Joint Undertaking (JU) and countries participating in the project under grant agreement No [101093169](#).

MS would like to thank Hessian Ministry of Higher Education, Research, Science and the Arts and the Federal Government and the Heads of Government of the Länder, as well as the Joint Science Conference (GWK), for their funding and support within the framework of the NFDI4Ing consortium. Part of this work was funded by the German Research Foundation (DFG) - project number [442146713](#). Part of this work was funded by the Hessian Ministry of Higher Education, Research, Science and the Arts - cluster project Clean Circles.

MB acknowledges support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2120/1 – [390831618](#).

## A Appendix

### A.1 An example master's programme for research software engineering

The target audience for such a master's programme would be students holding a bachelor's degree from a domain science, which we will call "home domain" in the following. There is explicitly no restriction on the candidates' home domain: it may be from the STEM disciplines, life sciences, humanities or social sciences. Candidates with a bachelor's degree in computer science are also explicitly included, although we acknowledge that their master's programme should include adaptations to make their interaction effective with other domain scientists. In order to give the future RSE the necessary breadth, we expect this to be a four semester curriculum.

The curriculum is formed from a combination of modules, some of which are core modules teaching essential skills that must be completed by all students. Other modules introduce more specialised concepts and skills. During the master's programme, students should pick an RSE specialisation from the list in this paper and attend these additional modules to deepen their knowledge in the field.

Core modules are of course drawn from the three pillars of the RSE and can be categorised accordingly.

- Software engineering skills:
  - Foundational module: Here we have an introduction to programming: Students learn at least two languages: a language that facilitates prototyping and data processing (e.g., Python or R) and a language for designing complex, performance-critical systems (e.g., C/C++). This exposes them to computers in a hands-on fashion and is the foundation for (DOCBB, LIBS).
  - Digital ecosystem module: Programming languages are not enough to work in a digital ecosystem, hence we require something like software craftsmanship, where tools like the Unix shell, version control systems, build systems, documentation generators, package distribution platforms, and software discovery systems are taught to strengthen skills in (LIBS, DOCBB, SWREPOS, SRU).
  - Software architecture module: Here we teach software design and software engineering, again strengthening (DOCBB, LIBS) on a more abstract level.
- Research skills:
  - Optional domain mastery module: Additional minor research courses, but students with a home-domain already have the research part well-covered.
  - Research tools module: Here we teach tools used to distribute and publish software, as well as introducing students to domain specific data repositories. Thereby gaining foundational knowledge in (SRU, SP, DOMREP).
  - Meta-research module: Here we teach people how research works. The research life cycle is introduced, as well as the data life cycle and the software life cycle are abstractly introduced.
- Communication skills:
  - Project management methods: Here we teach project management methods that are useful in science, such as agile ones (PM).
  - Communication skills module: Here we have courses focusing on interdisciplinary communication, interacting across cultures, communication in hierarchies, supporting end users effectively. These are all facets of the (USERS) skill.
  - Teaching module: This module covers topics to effectively design courses and teaching material for the various digital tools, thereby strengthening the (TEACH) skill.

Given that RSE work also involves a lot of craftsmanship skills, hands-on practice is an integral part of the curriculum. At least two lab projects are required within the mandatory curriculum. These should be executed as a team and involve a question from a domain science. We recommend covering both the candidate's home



domain and another domain of science. Ideally, projects stem from collaborations with scientists within the institution and RSE students take the role of a consultant. This setup strengthens the (TEAM, TEACH, USERS) skill and most likely also the (MOD) skill through interaction.

To emphasise the exposure to domains outside their bachelor's degree domain, we recommend that RSEs also support their non-home-domain project by supporting it with introductory courses from this discipline. We support the idea of broadening the interaction with other domains even more. This schools their ability to quickly adapt their vocabulary and thinking to other disciplines. This is an aspect of (MOD).

To align with the specialisations listed in this paper, example optional modules include topics on HPC engineering/parallel programming, numerical mathematics/scientific computing, web technologies, data stewardship, AI models/statistics, and community management/training.

The programme is finalised with a master's thesis which should be dual-supervised by an RSE supervisor from an actual project, and a domain supervisor. The thesis should answer a relevant research question (strengthening (NEW)) from the domain using computational methods. Software development is required, and the code is part of the gradable deliverables. The RSE supervisor ensures and grades the software craftsmanship aspects of the project. This setup ensures that we are grading the effectiveness of applying RSE skills in an actual research environment.

## A.2 An example of a possible career path

**Setting the stage** Meet Kay, Kim's younger sister [1] who currently studies researchology in a bachelor's programme in the established domain of researchonomy at University of Orithena (UofO). We will follow Kay's fictional career to illustrate how education, job-experience and a career in academic institutions could lead to become a successful RSE. In Kay's world, some of the measures proposed in this paper have already been implemented.

**Bachelor's degree** Through a program like Software Carpentry [53] or The Missing Semester [2], Kay learns about using computational tools to support the sophisticated statistical analysis typical for researchology. She uses those tools to create and automate the steps of processing data and producing outcomes for her bachelor's thesis (generating plots with matplotlib and even CI for automatic building) and takes pride in a fully open and reproducible bachelor's thesis enabling her to graduate with honours from the faculty of researchonomy.

**Master's degree** Kay ponders whether to continue with computational researchology, which her bachelor's supervisor is responsible for, or enrol in a domain-agnostic RSE master's programme. Researchers in computational researchology need to acquire a large part of the general RSE know-how presented in this paper and specialise in Quantum-Accelerated Bayesian Optimisation methods. However, Kay decides to go for the more generic route of a dedicated RSE programme because she wants to continue in academia, but does not like the idea of becoming stuck with one research topic. She also experienced the immediate satisfaction gained by helping colleagues from her research group with tricky technical problems, which makes her happier than the subdued sense of achievement from having a research paper accepted long after she had written it. For her, coding and sharing knowledge in the form of software is of similar importance to writing a paper focused mostly on the obtained results.

The domain-agnostic RSE Master programme consists of a core of RSE topics with various electives for specialisation, some of them domain-specific (e.g., chemistry) or topic-specific (e.g., cloud computing for research). Kay chooses digital archaeology and develops a pipeline for reconstructing 3D models from ground penetrating radar data, to simplify the process for archaeologists (reproducibility, big data, machine learning). The project management skills that are being taught as part of the core RSE curriculum really help her to not get lost in this project. Apart from working with the researchers in her archaeology group, she has to work with members of the central RSE department to help her with the pipelines. She also has to liaise with the central IT department to organise storage for the large data sets. Towards the end of the programme, she visits her first RSE conference where she sees a lot of notions (SWLC, RC) in action that so far have been abstract in her master's degree.

The exposure to the wider RSE community inspires her to invest additional time into her thesis to publish her software project under a licence approved by the Open Source Initiative and write an accompanying article in the open source journal JOSS[32]. Kay has now completed the RSE programme and has reached Junior RSE level.

**Junior RSE** Kay finds a position in the central RSE department at her university with a competitive IT salary. Although the contract is temporary, there is a good chance that it will lead to a permanent position. Kay completes

the Software Carpentry Instructor training and teaches basic research computing, while advising fellow students of her department on better programming (DOCBB and MOD skill). She also runs a seminar in the RSE Master’s programme. She publishes a condensed version of that in JOSE[31]. During her teaching duties, she becomes aware of a new project in her department that requires a community manager RSE, and she gladly signs up to focus more on her communication skills. After three years, she takes an exciting opportunity to work in another university.

**Senior RSE** The new position involves taking responsibility for the RSE related aspects of a large inter-organisational project involving different organisations. With her new responsibilities comes a shift in the importance of various aspects of her work. Having this position in an inter-organisational project places far more emphasis on communication and organisation skills. She is spending time teaching people (TEACH skill) to onboard them into the project. There is a lot of interaction with different stakeholders in the project like funders and user groups (USERS skill). To oversee the project, she uses an amalgamation of both agile and traditional project-management concepts and methods which she acquires on-the-job (PM skills). Her work so far has already been heavy on (TEAM) skills, but now also the leadership aspect comes into play.

**RSE-focused principal investigator** The job experience as a leading RSE for a large project was the last requirement necessary to be awarded the title of a “Certified Research Software Professional” (CRSP) from an institutionalised centre of RSE education. The certificate confirms her track record of valuable software contributions and of teaching and mentoring people, as well as her capability to enable, foster and contribute to high-quality research in a leading position. It is recognised by various funding agencies, such as the DFG, and hence enables RSEs to act as a Principal Investigator for RSE-focused grant applications. It is also recognised by many prestigious universities and opens many career options that are also typical for PhDs. Kay can now write her own grant proposals to effectively fund work of moving research software projects from prototypes to infrastructure.

## A.3 Existing frameworks

### A.3.1 HPC skills and certification

As an area that generally requires a range of advanced skills, High Performance Computing (HPC) is one field where there is ongoing work to identify relevant sets of skills for HPC practitioners and potential paths to develop these skills. The HPC Certification Forum [57] has developed a competence standard for HPC that defines a range of skills and how they are related in the context of a skill tree [34, 35]. This competence standard is currently being built upon by the CASTIEL 2 [15] project in collaboration with initiatives funded by the European High Performance Computing Joint Undertaking (EuroHPC JU) to create a framework for HPC certification [24]. While this framework focuses mostly on skills specific to HPC, there are a couple of similarities to the framework proposed in this paper. The “SD: Software Development” skill set is very similar to the software engineering skills discussed in Section 4, describing a wide range of such skills. This skill set contains Programming Best Practices (SD2), Software Configuration Management (SD3), Software Quality (SD5), Software Design and Software Architecture (SD6), and explicit mention of documentation (SD7, see our DOCBB). Besides the Software Concepts for HPC (SD1), which mainly concerns HPC-focused RSEs, most of the skills contained in the SD2-SD7 categories apply to all RSEs. A significant difference compared to the framework proposed in this paper is the absence of skills related to research or communication. Noteworthy is already now the level of detail in their skill tree which is more similar to Appendix A.1.

Also looking at pathways and how different skills are related, the UNIVERSE-HPC project [61], funded under the UK’s ExCALIBUR research programme [16], is looking to understand and develop training pathways to support the development of specialist skills in the HPC and exascale domains. The project is gathering open source training materials to develop curricula that support the training pathways that are underpinned by high-quality training materials.

### A.3.2 Bioinformatics skills and certification

Bioinformatics is another field that actively works on developing skill trees. The Bioinformatics Core Competencies [40, 63, 64], the BioExcel competency framework [39], the PerMedCoE competency framework [38], the Research Data Management and Data Stewardship competence framework [10] and the ELIXIR Data Stewardship Competency Framework for Life Sciences [51] are examples of grassroots efforts aiming at defining the set of skills of various bioinformatics specialities, one of them as a taxonomy [40]. These frameworks eventually converged into the EMBL-EBI Competency Hub [11, 37], where typical RSE and bioinformatician profiles at different

levels of seniority can be queried (e.g. Junior RSE<sup>16</sup>, Senior Computational Chemist<sup>17</sup>) and compared against one another (e.g. Junior vs. Senior RSE<sup>18</sup>).

Competencies can be divided into more fine-grained building blocks: knowledge, skills and abilities (KSAs). They can be organised in a taxonomy, and are also transferable, i.e. a KSA can be a prerequisite to multiple competencies. The Mastery Rubric for Bioinformatics [60] and the ELIXIR Data Stewardship Competency Framework for Life Sciences [51] are examples of KSA frameworks for bioinformatics curricula.

The Curriculum Task Force of the International Society for Computational Biology (ISCB) curates a database of degrees and certificates in bioinformatics [30, 40]. The database includes bachelor’s and master’s degree programs and specialisations, PhD programs, and certificates from graduate schools.

BioExcel has research competencies that combine some of our research competencies and some notions from the communication skills. Their computing competencies roughly map to our software skills. Here, we find competencies such as “package and distribute software”, which maps to our (LIBS) competencies, and “comply with licensing policy”, which would in our framework be part of (SP) in the research competencies. In addition, they have a dedicated parallel computing competency section, thereby shifting the emphasis of the knowledge of their computational tools towards the HPC-RSE specialisation in our framework. Career profiles, such as the computational chemist, bring additional domain specific knowledge; we would classify those as a mixture of DOMAIN-RSE and HPC-RSE. It is noteworthy, however, that the BioExcel framework puts very little emphasis on communication skills, which are often involved in RSE-related tasks.

## References

- [1] Hartwig Anzt et al. “An environment for sustainable research software in Germany and beyond: current state, open challenges, and call for action [version 2; peer review: 2 approved]”. In: *F1000Research* 9.295 (2021). DOI: [10.12688/f1000research.23224.2](https://doi.org/10.12688/f1000research.23224.2).
- [2] Anish Athalye, Jon Gjengset, and Jose Javier Gonzalez Ortiz. *The Missing Semester of Your CS Education*. MIT, Computer Science & Artificial Intelligence Laboratory. URL: <https://missing.csail.mit.edu/> (visited on 08/11/2023).
- [3] Michelle Barker et al. “Introducing the FAIR Principles for research software”. In: *Scientific Data* 9.1 (Oct. 2022), p. 622. ISSN: 2052-4463. DOI: [10.1038/s41597-022-01710-x](https://doi.org/10.1038/s41597-022-01710-x).
- [4] Christopher Blech et al. “SURESOFT: Towards Sustainable Research Software”. In: (2022). DOI: [10.24355/dbbs.084-202210121528-0](https://doi.org/10.24355/dbbs.084-202210121528-0).
- [5] Pierre Bourque, Richard E. Fairley, and IEEE Computer Society. *Guide to the Software Engineering Body of Knowledge (SWEBOK(R)): Version 3.0*. 3rd. Washington, DC, USA: IEEE Computer Society Press, 2014. 346 pp. ISBN: 978-0-7695-5166-1.
- [6] Neil Chue Hong. “Minimal information for reusable scientific software”. In: *2<sup>nd</sup> Workshop on Sustainable Software for Science: Practice and Experiences (WSSPE2)* (New Orleans, Louisiana, USA, Nov. 16, 2014). figshare, July 2014. DOI: [10.6084/m9.figshare.1112528](https://doi.org/10.6084/m9.figshare.1112528).
- [7] CodeRefinery. *CodeRefinery*. URL: <https://coderefinery.org> (visited on 06/16/2023).
- [8] *Collaborations Workshop 2023 (CW23)*. Software Sustainability Institute. URL: <https://www.software.ac.uk/cw23> (visited on 10/27/2023).
- [9] Council of Europe. *Protocol to the Convention for the Protection of Human Rights and Fundamental Freedoms (European Convention on Human Rights) as amended by Protocol No. 11*. Place: Strasbourg Publication Title: Council of Europe Treaty Series 155. 1988.
- [10] Yuri Demchenko and Lennart Stoy. “Research Data Management and Data Stewardship Competences in University Curriculum”. In: *Proceedings of the 2001 IEEE Global Engineering Education Conference (EDUCON)* (Vienna, Austria, Apr. 21–23, 2021). Ed. by Thomas Klinger, Christian Kollmitzer, and Andreas Pester. Red Hook, New York, USA: IEEE, Apr. 2021. ISBN: 978-1-7281-8478-4. DOI: [10.1109/educon46332.2021.9453956](https://doi.org/10.1109/educon46332.2021.9453956).
- [11] EMBL-EBI. *Competency Hub*. URL: <https://competency.ebi.ac.uk/> (visited on 07/20/2023).
- [12] ENCCS. *ENCCS lessons*. URL: <https://enccs.github.io/instructor-training/enccs-lessons/> (visited on 06/16/2023).
- [13] EuroCC. *EuroCC Training*. URL: <https://www.eurocc-access.eu/services/training/> (visited on 06/16/2023).
- [14] EuroCC National Competence Centre Sweden. *ENCCS - Supercomputer access and training for your business/organisation*. URL: <https://enccs.se/> (visited on 10/27/2023).

<sup>16</sup><https://competency.ebi.ac.uk/framework/bioexcel/3.0/profile/view/10115/alex-2>

<sup>17</sup><https://competency.ebi.ac.uk/framework/bioexcel/3.0/profile/view/10121/kim-0>

<sup>18</sup><https://competency.ebi.ac.uk/framework/bioexcel/3.0/profiles/compare/10115/10117>

- [15] EuroHPC Joint Undertaking. *EuroCC 2 and CASTIEL 2: Promoting HPC to boost digital skills, jobs and industrial competitiveness in Europe*. URL: [https://eurohpc-ju.europa.eu/eurocc-2-and-castiel-2-promoting-hpc-boost-digital-skills-jobs-and-industrial-competitiveness-europe-2023-02-03\\_en](https://eurohpc-ju.europa.eu/eurocc-2-and-castiel-2-promoting-hpc-boost-digital-skills-jobs-and-industrial-competitiveness-europe-2023-02-03_en) (visited on 06/16/2023).
- [16] ExCALIBUR. *Exascale Computing ALgorithms & Infrastructures Benefiting UK Research*. URL: <https://excalibur.ac.uk> (visited on 06/16/2023).
- [17] *Export Control in Science & Research*. Federal Office for Economic Affairs and Export Control (BAFA). URL: [https://www.bafa.de/SharedDocs/Downloads/EN/Foreign\\_Trade/ec\\_awareness\\_academia.html](https://www.bafa.de/SharedDocs/Downloads/EN/Foreign_Trade/ec_awareness_academia.html) (visited on 08/04/2023).
- [18] Deutsche Forschungsgemeinschaft. *Guidelines for Safeguarding Good Research Practice. Code of Conduct*. Apr. 2022. DOI: [10.5281/zenodo.6472827](https://doi.org/10.5281/zenodo.6472827).
- [19] R. Stuart Geiger et al. *So you want to start a data science institute? Achieving sustainability*. Software Sustainability Institute. URL: <https://www.software.ac.uk/blog/2018-04-05-so-you-want-start-data-science-institute-achieving-sustainability> (visited on 08/04/2023).
- [20] *General Data Protection Regulation*. EUR-Lex. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02016R0679-20160504&qid=1532348683434> (visited on 08/04/2023).
- [21] *German National Research Data Infrastructure (NFDI)*. German National Research Data Infrastructure (NFDI). URL: <https://www.nfdi.de/?lang=en> (visited on 07/14/2023).
- [22] German Research Foundation. *Merkblatt Programm Sachbeihilfe*. June 2023. URL: [https://www.dfg.de/formulare/50\\_01/50\\_01\\_en.pdf](https://www.dfg.de/formulare/50_01/50_01_en.pdf) (visited on 11/14/2023).
- [23] Don Gotterbarn, Keith Miller, and Simon Rogerson. "Software Engineering Code of Ethics is Approved". In: *Communications of the ACM* 42.10 (Oct. 1999), pp. 102–107. ISSN: 0001-0782. DOI: [10.1145/317665.317682](https://doi.org/10.1145/317665.317682).
- [24] Governing Board of the EuroHPC Joint Undertaking. *Amending the Joint Undertaking's Work Programme and Budget for the year 2023 (Work Programme and Budget Amendment no. 1)*. EuroHPC JU Decision No 03/2023. EuroHPC Joint Undertaking, Mar. 2023. URL: <https://eurohpc-ju.europa.eu/system/files/2023-03/Decision%203.2023.-%201st%20Amendment%20WP%202023.pdf>.
- [25] Morane Gruenpeter et al. *Defining Research Software: a controversial discussion*. Summary Report of FAIR4RS Subgroup 3 activity and discussion Version 1. FORCE11, Research Data Alliance, Research Software Alliance, Sept. 2021. DOI: [10.5281/zenodo.5504016](https://doi.org/10.5281/zenodo.5504016).
- [26] Helmholtz. *Helmholtz Federated IT Services (HIFIS)*. URL: <https://hifis.net> (visited on 06/16/2023).
- [27] Jane Henriksen-Bulmer and Sheridan Jeary. "Re-identification attacks—A systematic literature review". In: *International Journal of Information Management* 36.6, Part B (2016), pp. 1184–1192. ISSN: 0268-4012. DOI: [10.1016/j.ijinfomgt.2016.08.002](https://doi.org/10.1016/j.ijinfomgt.2016.08.002).
- [28] Simon Hettrick. *A not-so-brief history of Research Software Engineers*. Software Sustainability Institute. Aug. 2016. URL: <https://www.software.ac.uk/blog/2016-08-17-not-so-brief-history-research-software-engineers-0> (visited on 06/16/2023).
- [29] Päivi Hirvelä and Satu Heikkilä. *Right to Respect for Private and Family Life, Home and Correspondence. A Practical Guide to the Article 8 Case-Law of the European Court of Human Rights*. Intersentia, Oct. 2022. ISBN: 978-1-83970-323-2. DOI: [10.1017/9781839703232](https://doi.org/10.1017/9781839703232).
- [30] International Society for Computational Biology. *Degree & Certificate Programs in Bioinformatics*. URL: <https://www.iscb.org/iscb-degree-certificate-programs> (visited on 07/20/2023).
- [31] JOSE. *The Journal of Open Source Education*. URL: <https://jose.theoj.org/> (visited on 10/18/2023).
- [32] JOSS. *The Journal of Open Source Software*. URL: <https://joss.theoj.org/> (visited on 10/18/2023).
- [33] Matthias Katerbow and Georg Feulner. *Recommendations on the Development, Use and Provision of Research Software*. Zenodo. 2018. DOI: [10.5281/zenodo.1172988](https://doi.org/10.5281/zenodo.1172988).
- [34] Julian Kunkel et al. "The HPC Certification Forum: Toward a Globally Acknowledged HPC Certification". In: *Computing in Science & Engineering* 22.4 (2020), pp. 110–114. ISSN: 1521-9615. DOI: [10.1109/MCSE.2020.2996073](https://doi.org/10.1109/MCSE.2020.2996073).
- [35] Julian Martin Kunkel et al. "One Year HPC Certification Forum in Retrospective". In: *The Journal of Computational Science Education* 11.1 (Jan. 2020), pp. 29–35. ISSN: 2153-4136. DOI: [10.22369/issn.2153-4136/11/1/6](https://doi.org/10.22369/issn.2153-4136/11/1/6).
- [36] Carl Landwehr et al. "Software Systems Engineering programmes a capability approach". In: *Journal of Systems and Software* 125 (2017), pp. 354–364. ISSN: 0164-1212. DOI: [10.1016/j.jss.2016.12.016](https://doi.org/10.1016/j.jss.2016.12.016).
- [37] Marta Lloret-Llinares and Daniel Thomas Lopez. *The EMBL-EBI Competency Hub, a tool to support training and professional development*. FEBS Network. Oct. 2022. URL: <https://network.febs.org/posts/the-embl-ebi-competency-hub-a-tool-to-support-training-and-professional-development> (visited on 07/20/2023).
- [38] Marta Lloret-Llinares et al. "The PerMedCoE competency framework to guide the training programme". In: 29<sup>th</sup> Conference on Intelligent Systems for Molecular Biology and the 20<sup>th</sup> European Conference on Computational Biology (Virtual Event, July 25–30, 2021). July 2021. URL: <https://permedcoe.eu/publication/the-permedcoe-competency-framework-to-guide-the-training-programme/>.



- [39] Vera Matser. *BioExcel Deliverable 4.2 – Competency framework, mapping to current training & initial training plan*. Zenodo. 2016. DOI: [10.5281/zenodo.264231](https://doi.org/10.5281/zenodo.264231).
- [40] Nicola Mulder et al. “The development and application of bioinformatics core competencies to improve bioinformatics training and education”. In: *PLOS Computational Biology* 14.2 (Feb. 2018). Ed. by Olga G. Troyanskaya, e1005772. DOI: [10.1371/journal.pcbi.1005772](https://doi.org/10.1371/journal.pcbi.1005772).
- [41] Netherlands eScience Center. *What Is a Research Software Engineer? A Definition by the Netherlands eScience Center*. Tech. rep. Version 1.0. June 2023. DOI: [10.5281/zenodo.7994286](https://doi.org/10.5281/zenodo.7994286).
- [42] NFDI: Section Training & Education. German National Research Data Infrastructure (NFDI). URL: <https://www.nfdi.de/section-edutrain/?lang=en> (visited on 07/27/2023).
- [43] Abraham Nieva de la Hidalga et al. “The ENVRI Reference Model”. In: July 2020, pp. 61–81. ISBN: 978-3-030-52828-7. DOI: [10.1007/978-3-030-52829-4\\_4](https://doi.org/10.1007/978-3-030-52829-4_4).
- [44] PRACE. *Partnership for Advanced Computing in Europe*. URL: <https://prace-ri.eu/> (visited on 06/16/2023).
- [45] *Professionals in Computational Biomolecular Research*. (Visited on 10/30/2023).
- [46] *ReproHack Hub: Building Communities of Practice in Reproducibility*. 2023. URL: <https://www.reprohack.org/> (visited on 07/25/2023).
- [47] “Research Software (RS) Careers: Generic Learnings from King’s Digital Lab, King’s College London”. In: (). DOI: [10.5281/zenodo.2559235](https://doi.org/10.5281/zenodo.2559235). (Visited on 10/30/2023).
- [48] RSE Competencies Toolkit team. *RSE Competencies Toolkit*. GitHub. 2023. URL: <https://github.com/RSEToolkit/rse-competencies-toolkit>.
- [49] Tobias Schlauch, Michael Meinel, and Carina Haupt. *DLR Software Engineering Guidelines*. Tech. rep. Version 1.0.0. German Aerospace Center, Aug. 2018. DOI: [10.5281/zenodo.1344612](https://doi.org/10.5281/zenodo.1344612). Translation of *Software-Engineering-Empfehlungen des DLR*. Tech. rep. Version 1.0.0. German Aerospace Center, Aug. 2018. DOI: [10.5281/zenodo.1344608](https://doi.org/10.5281/zenodo.1344608).
- [50] Susan Schneegans, Tiffany Straza, and Jake Lewis, eds. *UNESCO Science Report: the race against time for smarter development*. Paris, 2021. ISBN: 978-92-3-100450-6. URL: <https://unesdoc.unesco.org/ark:/48223/pf0000377433>.
- [51] Salome Scholtens et al. *Final report: Towards FAIR data steward as profession for the lifesciences. Report of a ZonMw funded collaborative approach built on existing expertise*. Zenodo. Oct. 2019. DOI: [10.5281/zenodo.3471707](https://doi.org/10.5281/zenodo.3471707).
- [52] Judith Segal. “Some challenges facing software engineers developing software for scientists”. In: *Proceedings of the 2009 ICSE Workshop on Software Engineering for Computational Science and Engineering* (Vancouver, British Columbia, Canada, May 23–23, 2009). IEEE, May 2009. ISBN: 978-1-4244-3737-5. DOI: [10.1109/secse.2009.5069156](https://doi.org/10.1109/secse.2009.5069156).
- [53] *Software Carpentry*. URL: <https://software-carpentry.org/> (visited on 07/25/2023).
- [54] Stack Overflow. *Stack Overflow Developer Survey 2022*. en. 2022. URL: <https://survey.stackoverflow.co/2022#developer-profile-demographics> (visited on 08/10/2023).
- [55] *SureSoft*. TU Braunschweig, FAU Erlangen-Nürnberg. URL: <https://suresoft.dev/> (visited on 07/14/2023).
- [56] The Carpentries. *The Carpentries*. URL: <https://carpentries.org> (visited on 06/16/2023).
- [57] The HPC Certification Forum. *Competencies*. URL: <https://www.hpc-certification.org/cs/> (visited on 06/16/2023).
- [58] The HPC Certification Forum. *HPC Certification Forum*. URL: <https://www.hpc-certification.org> (visited on 11/01/2023).
- [59] *The Missing Semester of Your CS Education*. Massachusetts Institute of Technology. URL: <https://missing.csail.mit.edu/> (visited on 07/21/2023).
- [60] Rochelle E. Tractenberg et al. “The Mastery Rubric for Bioinformatics: A tool to support design and evaluation of career-spanning education and training”. In: *PLOS ONE* 14.11 (Nov. 2019). Ed. by Nicholas J. Provart, e0225256. DOI: [10.1371/journal.pone.0225256](https://doi.org/10.1371/journal.pone.0225256).
- [61] UNIVERSE HPC. *Understanding and Nurturing an Integrated Vision for Education in RSE and HPC*. URL: <https://www.universe-hpc.ac.uk> (visited on 06/16/2023).
- [62] Jing Wang. “Survival factors for Free Open Source Software projects: A multi-stage perspective”. In: *European Management Journal* 30.4 (2012), pp. 352–371. ISSN: 0263-2373. DOI: [10.1016/j.emj.2012.03.001](https://doi.org/10.1016/j.emj.2012.03.001).
- [63] Lonnie Welch et al. “Applying, Evaluating and Refining Bioinformatics Core Competencies (An Update from the Curriculum Task Force of ISCB’s Education Committee)”. In: *PLOS Computational Biology* 12.5 (May 2016), e1004943. DOI: [10.1371/journal.pcbi.1004943](https://doi.org/10.1371/journal.pcbi.1004943).
- [64] Lonnie Welch et al. “Bioinformatics Curriculum Guidelines: Toward a Definition of Core Competencies”. In: *PLoS Computational Biology* 10.3 (Mar. 2014), e1003496. DOI: [10.1371/journal.pcbi.1003496](https://doi.org/10.1371/journal.pcbi.1003496).
- [65] Igor Wiese, Ivanilton Polato, and Gustavo Pinto. “Naming the Pain in Developing Scientific Software”. In: *IEEE Software* 37.4 (July 2020), pp. 75–82. ISSN: 1937-4194. DOI: [10.1109/MS.2019.2899838](https://doi.org/10.1109/MS.2019.2899838).

- [66] Mark D. Wilkinson et al. “The FAIR Guiding Principles for scientific data management and stewardship”. In: *Scientific Data* 3.1 (Mar. 2016), p. 160018. issn: 2052-4463. doi: [10.1038/sdata.2016.18](https://doi.org/10.1038/sdata.2016.18).