A professorial view of PhD supervision in the light of doctoral training initiatives

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1. Introduction

Over the last decade in many European countries the modern doctorate is described as "determined by an interplay between professional research experience and personal development, the most important outcome of which is an individual trained to have a unique set of high-level skills [1]." This has led to a growth in structured doctoral programs, which are set alongside the doctoral training within "research intensive environments where excellence is fostered [1, 2]". This article outlines the professorial experience of doctoral training within an experimental physics group. It also describes the growth of wider professional development skills training arising from the research network NCCR MUST (National Center for Competence in Research Molecular Ultrafast Science and Technology). Some of MUST wider skills training was created within the equal opportunities program for this research network. The goal is to present a detailed picture of the outcomes of PhD training within a professor's group, whilst setting this within the context of other career development provisions now available. From the professor's viewpoint doctoral training within a group can develop independence, critical thinking, creativity and teamwork skills. The parallel career development programs offered by graduate schools and structured doctorates enhance the "transferable skills" of the doctoral candidates embedded in the research teams.

2. The role of professors

The core mission of our universities – and professors – is education and research. In the Swiss education system, a Bachelor's degree focuses on the basics in the different fields of expertise, and at ETH Zurich for example, there is strong emphasis on a broad mathematics education for all of our science students. Master's degrees aim to strengthen fundamental knowledge in a specific research area and, as such, bring students closer to the forefront of current knowledge in a focused field of research related to the expertise of appointed professors. Master students at ETH conduct a 6-month guided research project within an active research group.

Students who excel in the first two steps are often interested in research and continue to study for a PhD. Often these doctoral students come from all over the world. They have the opportunity to do cutting edge research under the guidance of a professor and group leader. This research often generates

results that advance our current knowledge horizon. PhD candidates learn that research is performed in a "learning by doing" environment alongside their professor, supervising senior scientists and post-docs, and working in teams with other PhD students.

The professors in leading the research in their groups set the vision, the goals, and select group members including the PhD candidates, senior scientists, postdocs, laboratory technicians, and office managers. They are responsible for generating sufficient research funding to cover the salaries of their team and the running expenses of their research. Necessary running costs for a group can vary in size depending on the research field – for example a theoretically-oriented professor may require investment in high level computers for modelling, while groups at CERN may require many millions of francs to build their state-of-the-art machines.

A professor is responsible for setting and maintaining the standard of the research done in his or her group, keeping it relevant to the field and the international competitive R&D activity. A professor's activities create undergraduate and master courses, graduated PhD students, trained post-docs with specific expertise, and a range of research outputs, published papers, conference presentations, and even industrial applications.

The excellence of a leading professor is key to developing knowledge horizons in research at world-leading universities, such as ETH Zurich. Professors are required to follow a high scientific standard in research and publications ensuring open access to all, beyond political borders and interests. With this open access professors stimulate each other to excel beyond our individual efforts – which supports faster progress – from which the entire human population can benefit. Leading research professors often pursue knowledge horizons which do not have an apparent or immediate commercial application, but history shows that eventually much of this knowledge may result in significant new economic activities, or medical breakthroughs, or even new conceptual ways of thinking – often in ways that were difficult and sometimes even impossible to predict. It is our mission to push the horizons of knowledge and share our findings openly, meaning that we have significant public responsibility and accountability for the research we generate.

ETH Zurich gives its professor competitive advantage by providing core funding in each field. We can conduct early feasibility tests, explore new opportunities and apply, from a strong position, for the competitive external funding opportunities. The benefits from this internal investment, or core funding, means that we compete well in the funding processes where success rates can be below 10%. It is also important not to forget that ETH Zurich, as a world-leading university, is set within a Swiss landscape and the research work generated from the university means that the university brings benefits to the community: Swiss students have access to a top-rated international university; we attract excellent international students who contribute to industry; we support Swiss industry by exploring limits and tackling fundamental challenges which introduce technological breakthroughs as early as possible; we increase international investments by drawing in companies with research labs such as IBM and Google; and we leverage the know-how of ETH Zurich to create successful spin-off companies.

New PhD students are embedded into this research landscape, within their chosen department, for approximately four years, the usual time allocated in Switzerland.

3. The organizational structure of the ultrafast laser physics group

This particular research group has been working in the field of experimental physics over the last twenty-five years at ETH Zürich. During that time more than seventy PhD students have graduated successfully.

Within the group the research is divided equally between applied and fundamental research, as are the PhD students. Applied research has meant looking for solutions to technological problems and fundamental research that was motivated by the professor's curiosity to see what happens when pushing measurement techniques into a regime where nobody has been before. For example, the research group has made many key innovations that enabled ultrafast lasers to be used for industrial applications [3]. On the fundamental research side, it has pushed the frontiers of ultrashort pulse generation enabling access to new observations on a timescale never accessed before [4]. During the research journey unforeseen challenges and problems are encountered, which need to be solved and very often open up new ideas and opportunities for the next research steps. Researchers become explorers who can uncover unexpected and unpredicted new opportunities. For example, the group demonstrated new world-record short pulse durations, we solved the problem that the transient electro-magnetic field within the short laser pulse is not stabilized, and the solution to this problem [5] not only enabled our community to

observe dynamics on 1000-times shorter time scale in the attosecond time regime (1 attosecond = 10^{-18} s) but also revolutionized frequency metrology with the frequency comb technology.

The whole research team is a crucial part of this effort. The professor compares her efforts to a small high-tech "business unit" where the professor is equivalent to the Chief Executive Officer (CEO) and the Chief Technology Officer (CTO). The group's "products" are courses and lectures, the graduated students, the experienced post-docs, and the research results, e.g. published papers and conference presentations. From the early days in the 1990s this group grew quickly to a size of approximately twenty-five people including PhD students, senior scientists, postdocs and a technician.

The key responsibility of the professor is to generate sufficient research funding to cover the salaries of the team and the running expenses of the research laboratories. ETH Zurich provides core-level financial support which is multiplied by successful applications to competitive funding schemes at ETH Zurich, the Swiss National Science Foundation (SNSF), European funding programs and industrial application. The more successful the research, the more additional resources can be acquired. All the PhD students are partially supported by these external funding sources. They have access to the proposals that elaborate the research plans for the next three to four years, which means that they are informed about the group's research mission. The PhD students and postdocs also support the education of Bachelor and Master students at ETH Zurich by working as teaching assistants.

Clearly there are key differences between the business unit model of an industrial effort and the research group. The PhD students acquire training and expertise over a four-year period and then the majority leave to take their skills to industry, the public and private sector and the academic system. The research group works continually to push the frontiers of knowledge in a world-wide competitive effort. The investment in the educational development of the PhD students justifies the core funding from universities, which acknowledges those efforts and the overall performance.

Every person in the group counts and we need people who are qualified, passionate about investigating the unknown and interested in striving for new findings. Research is never a straightforward process.

4. Selection process for PhDs to the group

All potential candidates are selected after a full-day's interview with the professor and group members. They are given the opportunity to visit the labs, meet the group members individually and to present the research work from their Master project. This selection process reveals the match between the candidate and the group, and also shows whether their level of expertise is related to the group's needs.

In experimental physics the research effort is based on a team work where each student is responsible for a certain task within a larger research team. Initially every new student works with a more senior PhD student to be given basic training in aspects of their work. At this stage they are introduced to the research procedures within a group in depth, with all the challenges, uncertainties and problem-solving skills needed. They learn that if an experiment doesn't go as planned, it could be due simply to a wrong cable connection or any number of other technical reasons – or it could even herald a wonderful new discovery! Working in a physics laboratory environment requires patience, continual learning and dedicated application to solve problems from small practicalities to fundamental challenges. This group is designed to create a state-of-the-art laboratory, which also has a supportive environment within the team, where people can achieve greater things than they could ever have imagined. The professor's motto is: nobody said it's easy, so try harder.

In an experimental physics group, as with any group, there is a wide range of experience levels, with some truly outstanding members who contribute to all levels of the team. The students who dedicate themselves early to striving for an academic career can often benefit from a wide engagement in a group's research. For example, whilst they give broad support to group members they also become co-authors of a wider range of publications as a result of their contributions. All PhD students are involved in every step along the research process starting from key component fabrication, to system integration and final performance characterization. This gives each student the opportunity to better understand their specific talents and interests. Experience shows that the teams self-organize to help each other.

It is a central goal that towards the end of the PhD time the students will be able to access knowledge about their own abilities and performance, which enables them to make the right choices for their next career steps in a way that combines their interests with their natural talents – ultimately doing something that makes them happy and successful.

5. The PhD student process and formal training within the group

All students who join the group read and sign a short document, which presents the group's operating principles with regards to scientific research efforts, scientific publication guidelines, attendance at conferences and overall lab safety measures. The number of rules is limited and focused by the overall goal of research excellence and intellectual freedom, which means that the rules remain practical and enforceable.

Every PhD student has the opportunity to attend an international conference within their first year, either with or without a paper or poster contribution. Afterwards they attend such conferences only if their submitted contributions have been accepted for an oral presentation. For certain conferences an accepted poster presentation is also considered sufficient. Joining the research process means learning that to achieve results takes time, depends on the central problem under investigation, challenges with the technology and whether you are working to establish a breakthrough. Resilience can be a quality developed in the process.

There is a particular emphasis placed on training students to develop and improve their scientific presentation skills. Sessions for practice talks, attended by the whole group, including the professor, precede all conferences. The outcome is that many students win the best student presentation awards at conferences, which are awarded both for an excellent research result and an excellent presentation.

A further experience in this group is the opportunity to learn to interact with the industrial sector – purchasing equipment for the laboratories, solving technical problems that develop in some of the larger machines and lasers, engaging in technology transfer processes and spin-off initiatives. This experience provides links to industry and gives personal development in solving the concrete problems that develop naturally while maintaining and running a state-of-the-art lab. External collaborations are coordinated and approved by the professor, but then all group members are also in direct contact with them, for example when their experimental work is underpinned by external international theory groups.

During the last year of the PhD period there is normally a formal meeting where a PhD student summarizes their goals leading up to the PhD exam. These meetings are often a real pleasure for the professor because the summaries are so well written. If anything, the only problem can be that these goals may be too ambitious within the short time frame, so it's the professor's task to give a realistic perspective here, in order for them to meet the PhD exam deadline.

The professor's philosophy is that over the PhD period a student will develop independence, self-management and challenge him- or herself intellectually and experimentally, which may involve some tough times finding a way through to scientific and practical solutions. An open-door policy means that all the students can approach the professor and/or can organize a meeting in advance. They are expected to be prepared and to produce a written summary of the current status, the problems and a first proposal of how a solution may be found. Very often this preparatory process points to solutions, or even a resolution in advance.

It gives the professor great pleasure to see the PhD students who excel in this environment. Often, they bring new ideas that went well beyond the initial proposals and some students even redefine their PhD research work. For a professor to see, in a young researcher's eyes, how much their independent efforts mean to them is a real pleasure. These are the students one encourages to continue within the academic system. It also positive to observe the others who move to successful jobs in industry and the commercial sectors, or even start their own spin-off company from the results obtained during their PhD, which is also explicitly supported by formal programs at ETH Zurich.

6. Training PhD students for transferable or professional development skills

The majority of universities provide formalized professional development courses, which can involve PhD training on presentation skills, report writing in English, laboratory safety, and assertiveness training. In certain universities there are specific university-wide doctoral programs providing this training, for example the University of Zurich's Graduate campus, for PhDs and postdocs [6].

The NCCR MUST program provided an opportunity to create specialist scientific provision and also professional development courses for PhDs in a network of eight Swiss universities. The concrete measures for doctoral training have been concentrated in an Annual Meeting with expert tutorial speakers, which also gives young scientists a place to communicate their research results to a wider community through presentations and poster sessions. Alongside there are outreach projects designed to develop PhDs' experiences in interacting with the public

and schools, thus building concrete career experience beyond the laboratory. PhD students have also organized well-attended summer/winter schools in specialist aspects of science, which were attended and supported by professors in the network. A future plan is to develop a specialist writing course for PhDs in physics and chemistry, working on both the general aspects of writing and the specific needs of the two disciplines.

The program to recruit, retain, and promote the women scientists in the network resulted in the design and running of a number of training skills workshops: managing your supervisor, finding a mentor, presentations skills, introduction to negotiation skills in a scientific environment, and the preparation of grant applications. A number of these workshops were held in a mixed gender setting, whilst others were women only. There are also regular career workshops, with experienced female scientists as role models, including professors at different stages of the career, and women who have moved into industrial careers.

7. Outlook

A new PhD student embedded within a group over the four years of a doctorate, particularly in fields such as experimental physics, has the opportunity to develop a range of independent skills, including a regular interaction with industrial firms, other academic groups, networks and the public. The development of independent thinking necessary for a successful PhD stands them in good stead, regardless of the subsequent career choices, which from this group range from positions in consultancy, banks, the optical and photonics industry, to new positions in academia.

However, given the scarcity of academic positions in general, it is clear that the majority of PhD students will move out of academia. It became a growing concern in the last decades, that doctoral training did not give a sufficient breadth of skills for the majority of PhD students moving into a wider economic sphere. This led to a European-wide move towards creating doctoral training schools or initiatives across all research fields [1, 2]. The establishment of these initiatives acknowledged the need for more formalized professional development training for all doctoral candidates; the "transferable skills", which will benefit them as they move into other sectors. This more formalized doctoral training aims to maintain research excellence in research groups, whilst giving independent training support to young researchers working within those groups.

In this context, it is important to remember that conducting cutting-edge and excellent research is the responsibility of the universities and the professors, and that the learning developed in the research process is also central to a PhD. Young people benefit from the opportunity of taking part in the creativity, challenges and uncertainty of the research process in itself. As we look to improve PhD supervision, and also formalize transferable skills training, we need to start from this premise. Different research disciplines present their PhD candidates with contrasting learning experiences and needs, which means that good supervision may have specific characteristics across diverse research fields.

In many European universities the responsibility for producing a successful, rounded PhD candidate, does not lie solely on the professor's shoulders, and is the result of a partnership with formalized professional development providers and doctoral initiatives. However, we must not undervalue the vital impact of conducting world-leading research, the excitement of being involved in this process, and the skills learned by the PhD student as a result.
World-leading universities, with their internationally recognized professors will provide a doctoral experience that is excellent for the PhD student embedded in their research group, whilst working in partnership with doctoral training initiatives that provide them with additional transferable skills for the next steps of their career. ■

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