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A review of bioinformatics education in Germany

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Abstract

We describe the establishment of bioinformatics in Germany and give an overview of current bioinformatics education in this country, from the perspective of the practitioner. The aim of this study is to demonstrate development of a strong bioinformatics education at German universities and research institutes during the last years. Beginning with a definition of the multi-disciplinary field bioinformatics, we give a survey of government initiatives in Germany in support of this field, which resulted in a wide spectrum of courses. To the best of our knowledge, we compile all ongoing courses at universities and research institutes. Five case studies featuring university courses with different educational focus illustrate the variety of efforts. In this context we also discuss the main components of German bioinformatics curricula. These components can be considered as the basic knowledge of German bioinformaticians. We conclude by giving perspectives for further development of bioinformatics education.

Keywords: *bioinformatics; education; Germany; master's degree; bachelor's degree; diploma; curriculum; DFG; BMBF*

INTRODUCTION

Historical overview and definition of the bioinformatics research field

Defining the scope of a research field is particularly important for a young field such as bioinformatics. A comprehensive definition is also very challenging, because just as in the life sciences, the scope of bioinformatics is changing constantly.

The term bioinformatics arose in the beginning of the 1990s, when large amounts of experimental data were produced by sequencing projects, particularly the Human Genome Project [1]. At that time, besides the development of databases, the development of algorithms for sequence alignment attracted attention to obtain further knowledge derived from genomic and protein sequences. By then, the basic algorithm for sequence alignment—the dynamic programming method—was already known. In fact, considering sequence analysis, the beginning of bioinformatics could be dated to the year 1970, when the publication of Needleman and Wunsch [2] marked the starting point for the development of many follow-up sequence alignment algorithms, refining and improving the basic idea. For example, more sophisticated gap handling [3] or variants such as local alignment methods [4] were introduced. New experimental data caused a need for new algorithms, particularly the introduction of statistics in bioinformatics as a crucial methodological component [5].

The history of drug design including quantitative structure activity relationship (QSAR) and ligand docking, which both represent fields with bioinformatics applications, goes back to the late 19th century [6, 7]. Since then, modern computer-aided methods have been developed, such as the Hansch analysis [8], docking tools [9, 10] and drug design tools [11, 12] resulting in the Flex tools [13, 14]. Another large sub-field of bioinformatics comprises

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protein [15, 16] and RNA [17, 18] structure analysis, classification and prediction.

Nowadays, an understanding of molecular systems is the main topic in experimental as well as in computational systems biology. Classical computational methods, for example, Metabolic Control Analysis, were developed in the 1970s [19, 20]. New techniques such as elementary mode analysis [21] entered the field. Several theoretical methods, for example, Boolean algebra [22], Petri net theory [23, 24] and many others brought new aspects into theoretical network analysis.

Following up on this short excursion into bioinformatics history, we define bioinformatics as a scientific field that solves problems in the biological sciences using computer science concepts and methods. We consider three main sub-fields, of which the first one covers sequence-related approaches, the second one is dedicated to structure-related (protein as well as RNA or DNA) methods, and the third one comprises the upcoming field of computational molecular systems analysis, which is related to molecular network analysis and computational systems biology. All three sub-fields have an overlap with biomathematics.

History of bioinformatics in Germany

Needless to say, it depends on the definition of bioinformatics at which point in time the first bioinformatics research and education was started in Germany. As one of the earliest examples, a Diploma course in biophysics [25] was established in 1970 at the Humboldt University in Berlin offering an education in theoretical biology with focus on computational systems biology.

Already in 1985, annual scientific meetings on bioinformatics started in Germany [26], leading to the timely buildup of a scientific bioinformatics community. The annual international German conference on bioinformatics (GCB) is dedicated to all topics in bioinformatics. Further crystallization points of bioinformatics research were the EMBL groups, one led by Pat Argos [27] and the other one by Chris Sander [28]. At the same time, new databases collecting genome and network data were developed in Germany, e.g. MIPS [29], BRENDA [30] and TRANSFAC [31].

Professional societies [German Chemical Society (Gesellschaft Deutscher Chemiker): GDCh; German Society for Chemical Technoloy and Biotechnology (Gesellschaft für Chemische Technik und Biotechnologie): Dechema; Society for Computer Science (Gesellschaft für Informatik): GI; Society for Biochemistry and Molecular Biology (Gesellschaft für Biochemie und Molekularbiologie): GBM; German Society for Medical Computer Science, Biometry and Epidemiology (Deutsche Gesellschaft für Medizinische Informatik, Biometrie und Epidemiologie): GMDS] established groups to coordinate bioinformatics research. Several funding initiatives by the government supplemented this development by installing bioinformatics research and education centers, which are described next.

Government funding initiatives in Germany

In spite of many research activities, education in bioinformatics as a field of study in its own was insufficient in Germany for a long time, leading to a significant shortage of bioinformatics scientists in academic and industrial research. Therefore, the German Research Foundation (DFG) (Deutsche Forschungsgemeinschaft) started a 5-years training initiative in 2000, funding programs in bioinformatics at the Universities of Bielefeld, Leipzig, Munich, Saarland and Tübingen. In the first 2 years, the DFG spent around 5 million EUR per year.

Table 1 summarizes the research and education goals of universities involved in this funding initiative. With one exception, all universities have implemented both bachelor's and master's courses in bioinformatics. The research themes cover the main topics in bioinformatics research, both sequence- and structure-based bioinformatics, but also the simulation of biological systems, ecological bioinformatics and applications in biomedicine.

To foster research activities and to achieve an even faster 'production' of well-educated bioinformaticians' the German Federal Ministry of Education and Research (BMBF) decided in 2001 to support the establishment of six bioinformatics competence centers with ~50 million EUR. The following centres with research agendas complementary to the DFG-funded universities were selected (Table 2):

(i) The Berlin Center for Genome Based Bioinformatics (BCB),
(ii) 'Genome Research and Medicine' at the Bioinformatics Competence Center Intergenomics in Braunschweig,
(iii) 'Interactions between Genomes of host and agent in bacterial infections' at the

Table 1: Overview of universities, funded by the DFG, including their research and education goals

Institutions	Research goal	Education goal
U of Bielefeld[a]	Focus on molecular bioinformatics, genome research (specifically of prokaryotes), ecological bioinformatics	BSc and MSc courses, on-line education
U of Leipzig[b]	Focus on self-organization of tissues, image processing, signal transduction and gene expression, genetic evolution	Bioinformatics as a course for computer science students
LMU[c] of Munich and TUM[d]	Genome bioinformatics, sequence-based and structural bioinformatics	BSc and MSc courses
Saarland U[e]	Specific focus on structural bioinformatics and drug design, particularly with medical applications	BSc and MSc courses
U Tübingen[f]	Developmental Biology, simulation of biological systems, biomedicine	BSc and MSc courses

The universities are listed in alphabetical order of the location.
[a]Universität Bielefeld.
[b]Universität Leipzig.
[c]Ludwig-Maximilians-Universität.
[d]Technische Universität München.
[e]Universität des Saarlandes.
[f]Eberhard Karls Universität Tübingen.

Table 2: Overview of the Bioinformatics Competence Centers funded by the BMBF, including their research and education goals

Institutions	Research goal	Education goal
FU Berlin[a], HU of Berlin[b], TFH Berlin[c]	Genome analysis, algorithmic bio-informatics, computational systems biology, structure analysis	BSc and MSc courses
TU of Braunschweig[d]	Databases, genome research, metabolome analysis	MSc course and minor field of study for computer scientists
U of Cologne[e]	Metabolome-driven bioinformatics, protein design	Postgraduate course
MLU of Halle-Wittenberg[f]	Plant bioinformatics, pattern recognition, network analysis	Diploma course
FSU of Jena[g]	Algorithmic bioinformatics, metabolic pathway analysis, game theory, alternative splicing	Diploma course, which is now converted into BSc and MSc courses
LMU[h] of Munich and TUM[i]	Functional analysis of mammalian genomes, sequential and structural bioinformatics	Diploma courses, BSc and MSc courses

The centers are listed in alphabetical order of the location.
[a]Freie Universität Berlin.
[b]Humboldt-Universität zu Berlin.
[c]Technische Fachhochschule Berlin.
[d]Technische Universität Carolo-Wilhelmina zu Braunschweig.
[e]Universität zu Köln.
[f]Martin-Luther-Universität Halle-Wittenberg.
[g]Friedrich-Schiller-Universität Jena.
[h]Ludwig-Maximilians-Universität.
[i]Technische Universität München.

Bioinformatics Center for Plant Genome research in Gatersleben and Halle,

(iv) 'Molecular communication of cells in Normal and Pathological state' at the Jena Center of Bioinformatics (JCB),

(v) 'Bioinformatics Center: Molecular Networks in Metabolism and Protein Function' at Cologne University and

(vi) 'Genome Annotation of Eukaryotes' at the Institute for Bioinformatics in Munich.

We created two maps of the German government-funded bioinformatics centers using Google Maps [32, 33].

BIOINFORMATICS DEGREE COURSES

As a result of the DFG and BMBF funding initiatives many bachelor's and master's courses in bioinformatics were established [34]. Table 3 lists

all universities offering courses in bioinformatics and biomathematics. The latter was included here, because of its large overlap with bioinformatics. Many bioinformatics methods use mathematical concepts, for example, statistics in sequence/structure analysis and in the study of microarray data, combinatorics in phylogentic tree inference and algebra/numerics in quantitative approaches.

Moreover, we distinguish between Universities and Universities of Applied Sciences designated with 'FH', which is the acronym of the German 'Fachhochschule'. The Universities of Applied Sciences provide a more application-oriented education including a strong collaboration with industrial partners.

Most of the courses were initiated in 2000 and 2001. At the Universities of Greifswald and Halle-Wittenberg, education in biomathematics/bioinformatics courses already began in 1998 and 1999, respectively.

According to the Bologna process [35], the classical 5-year German diploma courses, which combine a bachlor's and master's course in one single degree program, are converted into international bachelor's and master's courses. Thus, besides the newly established bachelor's and master's courses, also the German diploma courses can still be found, for example, at the LMU Munich.

Table 3 also gives an overview on the number and sub-fields of professorships for bioinformatics at German universities. The number of professorships in bioinformatics or related fields differs between universities. In Munich alone, the universities LMU and TU host six professorships in bioinformatics, indicating the importance of the field in this local area.

Many other universities hosting excellent bioinformatics research groups offer special courses in bioinformatics without providing a scientific degree in this field, for example, the Universities of Braunschweig, Dresden, Leipzig, Lübeck, and Potsdam. Some of them intend to establish a master's degree in bioinformatics. For example, the Universitiy of Braunschweig will implement a master's degree in bioinformatics with focus on metabolome analysis and computational systems biology.

Fees of bioinformatics degree courses

Until a few years ago, there were almost no study fees at all in German university education. Recently, some federal states introduced general fees of at most 500 EUR, for example, Baden-Württemberg, Bavaria, Hamburg, Hesse, Lower Saxony, North Rhine-Westphalia and Saarland. In comparison to other countries, these fees are still low.

BASIC BIOINFORMATICS CURRICULUM

In the following, we consider the topics and skills which are taught in nearly all bioinformatics curricula in Germany. Because bioinformatics is a strongly multi-disciplinary field, the basics in biology, mathematics and computer science are essential.

Bachelor's level

The Bachelor's curricula include basic courses in the above-mentioned fields to provide an understanding of problems and problem solving in biology as well as in computer science. Often, the courses in biology involve wet-lab exercises, for example, at the FSU Jena.

In computer science, principles of database design, algorithm design and analysis with a focus on pattern matching algorithms, dynamic programming and graph algorithms, are typical subjects of teaching. Moreover, programming paradigms and skills, mostly in a scripting language (Perl, Python) and in a higher level programming language (C/C++, Java) are included in the curricula. The necessary studies in statistics, linear algebra and graph theory represent the main topics of the mathematical part.

Teaching of the basic bioinformatics algorithms and data structures already starts at the bachelor's level. Generally, biological databases represent the first topic, followed by standard sequence analysis techniques, for example, dynamic programming or Hidden Markov Models. In line with our definition of bioinformatics, most curricula continue with structural bioinformatics, including protein structure classification and structure prediction for DNA and RNA. The computer science methods at this level are expert systems, supervised and unsupervised learning, and optimization algorithms such as genetic algorithms, simulated annealing, etc.

Master's level

At the master's level, specialization takes place to deepen the knowledge from the bachelor's courses. Here, we can observe a specialization according to the demands defined by needs from local researchers and industry. Thus, special topics such as algorithms

Table 3: Overview of existing bioinformatics study courses in Germany

University; study course name; URL	Degree	Since	Professorships for bioinformatics or related fields
FU Berlin[a]; Bioinformatics; http://www.inf.fu-berlin.de/stud/bioinf-stud/	D/B/M	2000	1. Algorithmic bioinformatics 2. Bioinformatics
TFH Berlin[b]; Bioinformatics; http://www.molgen.mpg.de/~koch.i/MScBI.html	M	2001–2004	1. Bioinformatics[A]
U of Bielefeld[c]; Bioinformatics and Genome Research; http://www.techfak.uni-bielefeld.de/BIG	B/M	2000	1. Bioinformatics and medical informatics 2. Biomathematics and theoretical bioinformatics 3. Genome informatics
FH of Bingen[d]; Bioinformatics; http://bioinformatik-bingen.de/	D (FH) B	2000	1. Bioinformatics[A]
U Frankfurt (Main)[e]; Bioinformatics; http://www.informatik.uni-frankfurt.de/studinfo/BIinfo.html	D	2003	1. Bioinformatics
U Freiburg[f]; Bioinformatics; http://www.bioinf.uni-freiburg.de/	M	2007	1. Bioinformatics 2. Experimental bioinformatics 3. Bioinformatics and molecular genetics
FH of Giessen-Friedberg[g]; Bioinformatics; http://kmubserv.tg.fh-giessen.de/pm/bi/	D (FH)	2001	1. Bioinformatics[A]
U of Greifswald[h]; Biomathematics; http://www.math-inf.uni-greifswald.de/biomathe.html	D	1998	1. Biomathematics 2. Bioinformatics[A]
MLU of Halle-Wittenberg[i]; Bioinformatics; http://www.verwaltung.uni-halle.de/STUDIUM/stualf/bioinf.d.htm:	D	1999	1. Bioinformatics 2. Bioinformatics and pattern recognition
U of Hamburg[j]; Bioinformatics; http://www.zbh.uni-hamburg.de/	M	2006	3 professorships at the Center for Bioinformatics, one is an associate professorship
FSU of Jena[k]; Bioinformatics; http://www.imb-jena.de/jcb/jcb.education.html	D	2000	1. Bioinformatics at Faculty of Computer Science 2. Bioinformatics at Faculty of Biology and Pharmacy
LMU[l] of Munich and TUM[m]; Bioinformatics; http://www.bio.ifi.lmu.de/index.html	D/B/M	2000	3 professorships for genome-oriented bioinformatics (TU) 3 professorships for bioinformatics (LMU) 3 of the six professorships are associate
FH of Oldenburg/Ostfriesland/Wilhelmshaven[n]; Biotechnology/Bioinformatics; http://www.technik-emden.de/studium/n/biotechnologie.php	B	2007	1. Bioinformatics[A]
Saarland U[o]; Bioinformatics http://www.uni-saarland.de/de/studium/studienangebot/bioinformatik	B/M	2002	1. Bioinformatics, 2 professorships 2. Bioinformatics and applied algorithms

(continued)

for molecular modeling and systems biology are now part of many curricula of master's courses.

High-throughput experiments continuously increase the demand for automatic data exploration, for example, of microarray data including statistical approaches. Computational data analysis techniques for experimental chip/array technologies or mass spectrometry become more and more important. Thus, algorithms for exploration of these data are part of the master's curricula. Due to the huge amount of gene expression data, qualitative and quantitative network analysis becomes ever more important. Apart from the teaching of classical ordinary differential equation (ODE)-based techniques, new methods such as Petri nets have been added to the master's curricula.

Table 3: Continued

University; study course name; URL	Degree	Since	Professorships for bioinformatics or related fields
U of Tübingen; Bioinformatics; http://www.zbit.uni-tuebingen.de/studium/	B/M	2005	1. Algorithms in bioinformatics 2. Simulation of biological systems
FH of Weihenstephan[p]; Bioinformatics; http://www.fh-weihenstephan.de/info/diplom/bi.html	D	2000	1. Bioinformatics[A]
TFH of Wildau[q]; Biosystems technology & Bioinformatics; http://www.fachhochschule.de/FH/Studium/Biosystemtechnik&Bioinformatik.2040.htm	B/M	2001	1. Bioinformatics[A]

The university name and the name of the course, the degree, the date of establishing the course and a URL are given. Degrees offered are indicated by the following abbreviations: D-Diploma, B-Bachelor, M-Master. To give the status of the professorship, we write an [A] for an associate professorship (in Germany C2, C3, or W2); the others are full professorships (C4 or W3).
The universities are listed in alphabetical order of the location.
[a]Freie Universität Berlin.
[b]Technische Fachhochschule Berlin.
[c]Universität Bielefeld.
[d]Fachhochschule Bingen.
[e]Johann Wolfgang Goethe-Universität Frankfurt am Main.
[f]Albert-Ludwigs-Universität Freiburg.
[g]Fachhochschule Giessen-Friedberg.
[h]Ernst-Moritz-Arndt-Universität Greifswald.
[i]Martin-Luther-Universität Halle-Wittenberg.
[j]Universität Hamburg.
[k]Friedrich-Schiller-Universität Jena.
[l]Ludwig-Maximilians-Universität.
[m]Technische Universität München.
[n]Fachhochschule Oldenburg Ostfriesland Wilhelmshaven.
[o]Universität des Saarlandes.
[p]Fachhochschule Weihenstephan.
[q]Technische Fachhochschule Wildau.

Some curricula, for example at the TFH Berlin, involve lecture series, in which topics and lecturers vary each semester, addressing ongoing work and highlighting current needs in industry and research.

CASE STUDIES

We briefly describe five case studies, which represent typical, but different, examples for the development of bioinformatics education in Germany. These five scenarios correspond to very different funding situations, covering typical cases and giving an exemplary overview of bioinformatics education in Germany.

Unfortunately, it is not possible to cover all of German bioinformatics in this paper. To be representative, we chose one of the earliest DFG-funded centers that provides bioinformatics education—the University of Bielefeld; two BMBF-funded centers—the BCB center in Berlin and the Jena Center of Bioinformatics; and two other universities that did not receive specific funding. These are the University of Greifswald with a tradition in biomathematics and the University of Münster, which has recently established a professorship for bioinformatics.

Our five case studies highlight the diversity of efforts towards bioinformatics education in Germany. Some differences arise from the local academic environment: Berlin consists of a large complex of universities and research institutes, whereas other universities are comparatively small. Other differences originate from the intentions behind the creation of the program: the course at the Humboldt University Berlin follows up on an old tradition, whereas the 'computer science in the natural sciences' program in Bielefeld was started based on the recommendation of the federal state to offer a computer science degree with some unique characteristics. As a consequence, the depth and focus of the programs vary considerably. Small specialization areas in bioinformatics can be found at some universities, while others offer the full spectrum of BSc, MSc and a graduate school (PhD), (Tables 1, 2 and 3). This diversity of approaches should be considered as a strength, as long as a

common framework defines a set of standards that is shared by all programs.

The Berlin Center for Genome-based Bioinformatics (BCB)

With the BMBF initiative several educational programs were established in Berlin involving Free University (FU), Humboldt University Berlin (HUB), Technical University of Applied sciences (TFH), Max Planck Institute for Molecular Genetics (MPIMG), Max Delbrück Center of Molecular Medicine (MDC), Charité, and Zuse Institute Berlin (ZIB). Scientists from universities, Max Planck institutes and other research institutions in Berlin are involved in teaching activities in bioinformatics.

The Free University Berlin has implemented a consecutive bachelor's and master's program focusing on theoretical computer science approaches in bioinformatics such as algorithm development and statistical methods. The bachelor's and master's programs both started in the winter semester 2000. In the bachelor's program, which is designed for 60 students and runs six semesters, the fundamentals in mathematics, computer science, biochemistry/chemistry and physiology are taught. In summer 2003, the first students finished their bachelor's degrees. The master's program, which is designed for 25 students, and runs three semesters, deepens the comprehensive knowledge in certain fields such as biological and chemical networks, biological and physical modeling, storing and analyzing genome and proteome data, and analysis and visualization of biological mass spectrometry data. An important aim is the promotion of excellent students for further studies in special PhD programs. Per year, about 30 students are finishing the bachelor's course and 10–15 students the master's course.

At the Technical University of Applied Sciences Berlin, a more application-oriented master's course in bioinformatics for graduates of biological and medical sciences has been initiated successfully. It started in the winter semester 2001 and runs also three semesters accommodating 20 students. The courses attracted an increasing number of students from all over the world. The first master students graduated in 2002. The emphasis is both mathematics (with focus on statistics) and computer science (algorithms, database methods, programming techniques, data mining). Based on this knowledge the following bioinformatics approaches are taught: sequence and structure analysis, statistics in biology and medicine, graph-theoretical network analysis, and Petri net approaches in systems biology. In total, 40 students finished this special master's course.

The Humboldt University of Berlin has introduced bioinformatics education in the diploma course in biophysics and bioinformatics and in computer science. In 2000, the Humboldt University founded the Center for Theoretical Biophysics and Bioinformatics (BPI) with the aim to coordinate the activities of several research groups of the Faculties of Mathematics and Natural Sciences I/II and the Medical Faculty. The center is based on the biophysics program, existing since 1970, and combines it with a more intensive education in computer science and bioinformatics.

In 2004, an 'International Max Planck Research School (IMPRS) for Computational Biology and Scientific Computing' has been established at Max Planck Institute for Molecular Biology and FU Berlin [36], which gives excellent students from all over the world the opportunity for doing PhD research. The course accommodates up to 20 students every year.

Additionally, the Max Planck Institute for Molecular Genetics provides an online education in bioinformatics [37].

University of Bielefeld

Bioinformatics education at the University of Bielefeld started in the early 1990s in the joint Department of Computer Science and Biotechnology ('Technische Fakultaet'). In particular, a series of lectures 'algorithms for sequence analysis' was developed in the latter as part of the specialization curriculum for the diploma (equivalent to MSc) in 'computer science in the natural sciences' that was established in Bielefeld at that time. Shortly thereafter, courses in 'sequence analysis with distributed resources' (SADR [38]; refurbished in 2006) and an international online course in biocomputing [39] were added, in response to the shortage in bioinformatics training opportunities at that time.

Bioinformatics then entered an exponential growth phase when its relevance for genome sequencing projects became apparent. Joint grant applications of the Technische Fakultät and the Department of Biology resulted in participation in the DFG bioinformatics initiative, supplemented by

funds from federal and state sources. This led to the creation of institutes for bioinformatics and genome research, which are now the crystallization points for several degree programs in bioinformatics on the bachelor's, master's and PhD level. About 19–26 students per year receive a bachelor's degree and about 10, a master's degree.

Also, the University of Bielefeld runs an 'International Graduate School in Bioinformatics and Genome Research' [40], accommodating 30–40 PhD students. Interdisciplinary cooperation is very strong. Typically, a PhD student has two advisors, one in biology and one in bioinformatics or computer science.

Within all these programs, a wide variety of courses, seminars and labs are currently offered, ranging from elementary sequence analysis and biomathematics to advanced topics such as algorithms for reconstructing genome evolution, for pathway analysis or RNA gene prediction and motif search.

The Bielefeld Bioinformatics Education web server offers teaching material and other resources [41, 42].

Ernst-Moritz-Arndt University of Greifswald

At the University of Greifswald, bioinformatics is part of the biomathematics education and is represented by one professorship (held by one of the authors). Teaching is focused on practical exercises and a lecture on molecular evolution. Bioinformatics in Greifswald was established in 2006 in response to demand from students within the biomathematics diploma program, which is unique in Germany, enabling students to design and apply mathematical methods and models in biology and medicine. In this context, bioinformatics provides a topical and in-demand application area in particular for diploma theses. Furthermore, bioinformatics is becoming embedded in the Greifswald university focus on life science, and functional genomics in particular. Here, the demand for collaborative work, especially from the medical department, is very high.

The bioinformatics sub-program will be integrated into the forthcoming bachelor's and master's degree courses in biomathematics, and is expected to include teaching on molecular evolution, transcriptomics, and sequence and network analysis, in the form of lectures, practical exercises and theses.

'Molecular communication of cells in Normal and Pathological state', Jena Center of Bioinformatics (JCB)

In 2000, before the foundation of the JCB in 2001, a diploma curriculum in bioinformatics was established at the University of Jena. The School of Mathematics and Computer Science as well as the School of Biology and Pharmacy installed one professorship for bioinformatics each, whose labs are located on the same floor, fostering the collaboration between the groups.

The curriculum is based on two pillars, the first covers mathematics and computer science and the second biology. The courses include the following topics: (1) the bioinformatics module with a theoretical and an applied part; (2) the biology and biochemistry/molecular biology module containing genetics and biochemistry; (3) the theoretical and applied computer science module covering algorithms, computability and complexity, data structures, and programming techniques and (4) the mathematics module with discrete mathematics, logics, linear algebra, analysis and statistics. Additional modules are available, for example, special seminars in bioinformatics, biochemistry and molecular biology, specific training in biology of organisms, training on data mining and sequence analysis, practical training in molecular biology, and programming training. The continuing courses are focused on special research fields existing in Jena. Particularly the analysis of metabolic networks plays a crucial role, but also genome analysis, structural biology and systems biology.

The curriculum is designed for 35 students, who are accepted based on a personal interview. Currently, about 15 to 20 students per year leave the university with a diploma degree in bioinformatics.

The government-funded JCB represents one building block in the bioinformatics research landscape in Jena, involving an EU-funded Center for Design and Structure in Biology, the SFB (Sonderforschungsbereich—a special funded research area), 'multifunctional signal proteins', the Interdisciplinary Center for Clinical Research and Scientific Computing, and also small companies. Collaboration with the JCB gives rise to many PhD theses at the university.

University of Münster

At the University of Münster, bioinformatics can be studied as a specialization area only, typically in biology and computer science on the newly established bachelor's or master's level. One chair in bioinformatics was established in 2003 in the department of biology, now part of the 'Institute of Evolution and Biodiversity'. It offers modules in bioinformatics with a focus on evolutionary issues of protein and RNA, on networks of biological entities and on simulation. A course in computer science is a requirement for all students of biology.

Generally, bioinformatics education in Münster is characterized by a strong interaction with experimental evolutionary biology. Theses in bioinformatics are often obtained in a collaborative setting between bioinformaticians on the one hand and biologists or computer scientists on the other hand.

Most recently, Münster was one of the awardees of a Volkswagen Foundation grant to foster teaching of evolution, with an emphasis on computational work. In the Medical Faculty, there is an interest in bioinformatics since 2001. A newly appointed bioinformatics chair will strengthen bioinformatics education in the near future.

CONCLUSIONS

In this paper, we described the development of education and research in the field of bioinformatics in Germany. Based on the DFG and BMBF funding initiatives supporting German universities and scientific institutions and based on the concerted effort of researchers from different fields such as biology, computer science, mathematics and chemistry, a wide spectrum of bioinformatics education and research was established within just a few years.

Academic degrees, such as the German diploma and the German doctorate (equivalent to the PhD), as well as internationally recognized bachelor's and master's degrees can be acquired in many German universities. As in the UK [43], in Germany the introduction of full undergraduate programs in bioinformatics together with graduate courses at all educational levels led to a new generation of well-educated bioinformaticians in industry, universities, and research institutions performing high-level research in bioinformatics and related fields.

The German educational system is in a state of transition, in particular in response to the Bologna process [35]. In Germany, bioinformatics is a forerunner in terms of sustained funding, English as a teaching language and the diploma to BSc/MSc transition. Since tuition fees are still not taken or are at least low in comparison to other countries, obtaining a bioinformatics education in Germany at all levels from BSc to PhD, can be expected to yield high returns on investment. Student research opportunities are exciting, because the field was, and still is, fostered by strong government support and is backed up by a pharmaceutical and biotechnology industry with a long tradition and a global impact.

Germany is closely allied with other countries featuring a strong bioinformatics education such as the US, the UK [43] and many other European countries. In this community, the exchange of students and the mobility of faculty gradually improve education on the international level. A concerted effort towards improving education in bioinformatics can be observed, leading to a growth of the field worldwide.

With the huge amount of new data on molecular systems gained from high-throughput experiments, a holistic comprehension of biological systems becomes a new focus in biological research, known as systems biology. In this field, bioinformatics techniques play a crucial role. Thus, computational methods in systems biology are also part of bioinformatics education. There is still a lack of computational methods in bioinformatics as well as in systems biology, for example, for the visualization of biochemical networks and the qualitative and quantitative analysis of large networks. These shortcomings are being addressed by many of the bioinformatics centers we mentioned. Moreover, following the spirit of the initiatives in bioinformatics education we described, Germany is starting to establish new initiatives focused on systems biology in research and education. Examples are the BMBF systems biology funding efforts, one focusing on hepatocytes HepatoSys [44] and the other one on research and education units of systems biology—FORSYS [45]. The latter one will be funded with 70 million EUR. In both programs the development of new computational approaches is one main focus.

Based on the experiences made with the establishment of bioinformatics education, the new initiatives are expected to yield a thriving effort of systems biology education and research, overlapping with the field of bioinformatics.

Key Points

- In Germany a rich and diverse landscape of bioinformatics education exists.
- Bioinformatics education has been successfully initiated by specific governmental programs within the last years.
- Apart from basic knowledge in biology and computer science, local specialization allows for diversity in research and education in bioinformatics.
- Overlapping with bioinformatics, systems biology is now a target of major government funding initiatives.

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