



CENTRAL EUROPEAN UNIVERSITY

Department of Mathematics and its Applications

## **PhD Student Handbook**

Program established in 2001

Program Accreditation

Program approved and registered by the New York State Education Department

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## **Overall aims of the program**

The PhD program Mathematics and its Applications is in cooperation with the Alfréd Rényi Institute of Mathematics, Hungarian Academy of Sciences, home of Abel Prize laureate Endre Szemerédi. The Ph.D. program is designed for individuals who demonstrate the potential to perform original research under guidance in mathematics, with a view to various careers, including those in research and teaching. Expertise of the faculty include algebraic geometry, combinatorics, functional analysis, group theory, low dimensional topology, number theory, partial differential equations, representation theory, theory of algorithms.

As a community of students, faculty and staff, the Department of Mathematics and its Applications is committed to academic freedom, equal access to education and collegial self-governance. Our ultimate aim is to enable our diverse student body to become successful and influential professional scientists in the future social and academic life of their home countries and abroad.

## Doctoral Program Committee (Math DPC)

The Doctoral Program Committee (Math DPC), nominated by the Head of the Department of Mathematics and its Applications and approved by the UDC, consists of a chair, who is a member of the Department of different from the Head, and at least two members of the Department, moreover a student representative chosen by the PhD students at the beginning of each Academic Year.

Quorum is simple majority; voting is done by simple majority; in case of equal number of votes, the vote of the Chair of the Math DPC decides.

When the nature of the case allows (for example, a decision has to be made with simple voting), decisions can be made through emails.

In cases not covered by the PhD Handbook, the Math DPC reserves the right to review and resolve the cases individually, in consultation with the UDC.

### Program learning outcomes

Prospective PhD students are expected to possess a good knowledge of the fundamentals in mathematics, especially in algebra and analysis in the areas described in the Annex 2.

The learning outcome of the Mathematics and its Applications PhD program can be classified into three major clusters: **knowledge**, **skills** and **attitudes/values**.

#### Knowledge

- Advanced knowledge in four fundamental areas of mathematics, Algebra, Analysis, Combinatorics and Geometry/Topology,
- State of the Art knowledge in the student's specific area of research,
- Possessing the fundamentals tools and the way of their use in the student's specific area of research,
- Ability to measure the difficulty of a mathematical problem, and to identify promising approaches and tools for the solution,
- Understanding the interdisciplinary aspects of scientific research, like connections of the student's specific area of research to other fields in mathematics, science or social sciences,
- Wherever it is possible, learning about applications of mathematical research.

#### Skills

- Ability to organize the solution of a mathematical problem into suitable smaller tasks,

- Ability to cooperate with fellow researchers,
- Ability to communicate ideas orally,
- Ability to present a mathematical topic orally either to experts, or to a wider mathematical audience,
- Ability to present own ideas in writing in a way such that it is accessible to fellow researchers,
- Ability to work in teams,
- Ability to organize a task, to set out priorities.

### **Attitudes/values**

- Highest international standards in research and teaching,
- Promotion of openness, self-reflection, and critical thinking. Pursuit of truth wherever it may lead, and resolution of differences through debate, not denial.
- Interdisciplinary and problem-focused approaches to teaching and research,
- Preserving a multiple intellectual identity by the diversity of students,
- Educating students to be citizens of the world, connected to their own communities and to others different from themselves.

## **Admissions**

Students seeking admission to our PhD program have to meet both the general CEU application requirements and the requirements of the Mathematics Department, as follows.

### **General CEU Admissions Requirements**

are available at <http://www.ceu.hu/admissions/requirements>.

### **Specific Requirements of the Mathematics Department**

**1. Eligibility Requirements:** Students from any country may apply. Applicants are expected to have earned a master's degree (or equivalent) in mathematics or a related field (physics, computer science, engineering, economics etc.) from a recognized university or institution of higher education, or provide documentation indicating that they will earn such a degree by the time of enrolling in our PhD program. We also accept excellent candidates with a bachelor's degree only, if they have completed at least four years of college by the time of enrolling, and have a strong mathematical background.

**2. Statement of Purpose:** Applicants are required to submit a one-page statement describing their interest in mathematics, their achievements and future goals.

**3. Mathematics Entrance Examination or GRE:** Applicants have to prove familiarity with the basic material in algebra and analysis, by taking either a Mathematics Exam (for a list of subjects to be covered on the exam see Annex 2) or the GRE Subject Test in

Mathematics(scanned copy of the test score sheet is to be submitted at application, and enrolled students are required to submit official language and program specific score reports.). In addition, candidates passing the threshold set by the department for the written tests will be interviewed (on the basis of the list of subjects of in Annex 1).

Various students, whose number is determined by the CEU administration, who are admitted into our PhD program are eligible to receive full CEU Doctoral Fellowship for three years. Doctoral enrollment may continue up to a maximum of six years. The CEU fellowship award covers tuition, the student activity fee, medical insurance, and provides a full living scholarship.

Strong candidates who submit complete application packages and provide documentation that they are able to support themselves may be admitted for an additional number of places, if they satisfy the same entry requirements. Transfers from other institutions' doctoral programs to our PhD program are also possible in exceptional cases.

The admission process is conducted by the Admission Committee, which is appointed by the University Doctoral Committee, based on the recommendation of the Doctoral Program Committee.

## **Doctoral (PhD) Program Structure and Graduation Requirements**

<b>Degree offered:</b>	<b>PhD in Mathematics and its Applications</b>
<b>Length of study:</b>	<b>3 – 6 years</b>
<b>Graduation requirements:</b>	<b>90 CEU credits (ECTS credits: 180)</b> (36 course credits for grade + 52 research credits+ 2 credits extracurricular activity), and courses for audit worth 6 credits, and <b>dissertation</b>
<b>Language of instruction:</b>	<b>English</b>

**Summary of the requirements during the PhD program** (see below for more details)

*First Year, so called Probationary PhD students*

- 18 CEU course credits (equivalent of 6 courses, out of which 4 are mandatory courses in Algebra, Functional Analysis, Combinatorics, and Geometry/Topology),
- passing the Comprehensive Exam measuring a basic understanding of the material of three of the four mandatory courses,
- active participation at the PhD Student Seminar,
- preparing a thesis proposal in the selected area of research,
- passing the Candidacy Exam measuring a basic understanding of the selected area of research.

*Second and Third Year students, so called Doctoral Candidates*

- 18course credits for grade (or as much is left to have 36 credits in total),
- audit courses for 6 credits,
- active participation at the PhD Student Seminar,
- supervised research,
- extracurricular activities.

*By the end of the sixth year (preferably by the end of the fourth year)*

- dissertation defense.

### **Residency requirements**

Doctoral (PhD) students have to reside in Budapest during the first 3 years of study. They are expected to remain in contact with campus academic life and respond to any communication from their department within 24 hours.

Exemption from the residency requirement can be granted by the Math DPC, for example for purposes of conference visits or at most one Academic Year long scientific trip in the student's third year related to the student's study, or, in exceptional cases, for urgent family or medical reasons. Any absence of a week or longer should be reported to the Math DPC and permission should be asked.

In case of unreported or unjustified absence, the Math DPC can initiate the suspension of the doctoral stipend.

### **Short Description of the Doctoral (PhD) Program**

Our PhD program comprises coursework, research and dissertation components. Its duration is 3-6 academic years. The ideal situation is when a PhD student accomplishes the whole coursework and completes her/his dissertation within 3 years from the date of enrollment. The (maximum) 6-year period, between the date of enrollment and the date of dissertation submission, allows enough flexibility for our students. In their first year, called *Probationary Period*, students have the status of *Probationary Doctoral (PhD) Candidates*. During this period they earn at least 18 course credits, write a dissertation proposal, and take the *Comprehensive Exam* covering three of the mandatory courses, including Analysis and Algebra, as well as the *Candidacy Exam* whose material is worked out by the advisor, and approved by the Math DPC. After students pass these exams they have the status of *Doctoral (PhD) Candidates* and focus mainly on research towards the PhD dissertation, under close supervision. More details are provided below.

The department offers courses in various parts of mathematics and its applications. The regular courses are delivered during the two main terms, Fall and Winter Term, that start the second half of September and early January, respectively (and each of them has a duration of

12 weeks). Each course during Fall and Winter term is worth 3 credits. There also are special courses and invited lecture series scheduled beyond these two terms, especially during the Spring Term.

PhD students have to earn at least 36 credits for grade in mandatory and elective courses, and take 6 credits for audit, usually on the supervisor's recommendation. Credits earned by courses taken at another university during the Second or Third year of study may count upon the approval of the Math DPC, and subject to the credit transfer policy of CEU. Note that 1 credit = 12 x 50 minutes = 600 teaching minutes at CEU. It is required to take at least 18 credits for grade in the first year, including all mandatory courses. The remainder of the required course credits for grade is taken in the second and third years. Students are also required to earn 52 research credits.

PhD students at the Department of Mathematics and its applications may choose the **Network Science Track**. In this case 8 elective course credits for grade are provided by the Network Science Center.

### **Probationary Period**

Starts on the date of enrollment and terminates when the Candidacy Exam is successfully passed by the end of the first year. Probationary Doctoral (PhD) Candidates have to reside in Budapest for the duration of the academic year.

#### *First Year Coursework*

In the first year, a PhD student has to earn at least 18 course credits for grade, including the 4 mandatory courses: *Topics in Algebra*, *Topics in Analysis*, *Topics in Combinatorics*, and *Topics in Topology and Geometry*. Among the required course credits, each student has to earn at least 6 credits for grade in elective courses, which help to find the direction of future research, and partially prepare the forthcoming PhD dissertation. At most one of these courses might be a mandatory MS level course upon the recommendation of the advisor, in case the student's background requires it.

Taking more than 4 courses for grade a term is discouraged, and requires the Head's approval.

Instructors provide students with syllabi, which include in particular the dates and forms of examination (quizzes, midterm and final exam, classroom presentations, etc.) as well as the formula which gives the final grade. The minimum passing grade for any course is C+ (worth 2.33 out of 4.00). Note that our university uses the US grading system. For further details, please visit <http://www.ceu.hu/node/5360/572>, Section *Student Rights, Rules and Academic Regulations*.

#### *PhD Student Seminar*

Probationary PhD Candidates, Second and Third year PhD students are encouraged to attend regularly the PhD Student Seminar sessions which take place weekly during the Fall and Winter Term. Colloquium lectures, which are part of the PhD Student Seminar, are



mandatory. The PhD Seminar is worth 4 credits per academic year (2 credits per term) for a Pass/Fail qualification for a contribution to the seminar, which might be for example active participation, or giving a talk, or preparing a note (preferably in a group) about a talk at the Seminar. It is mandatory to give one talk at the PhD student seminar during the Second or the Third year of the program preferably about the student's own work.

This seminar aims to offer our mathematical community (students, faculty members and visitors) a proper framework for discussions on various topics in mathematics and its applications. The colloquium lectures are public lectures accessible to all students given by our faculty members or visitors.

### *Dissertation Proposal*

Soon after enrollment, every probationary PhD candidate is assigned an *advisor* (or *early supervisor*) by the Math DPC. The advisor's role is primarily to help the student in choosing an adequate research topic and preparing a Dissertation Proposal. The proposal should be 3-5 pages long and should contain:

- title of research work
- name of student
- name of advisor
- general presentation of the subject
- research problem(s) and intended results
- short description of previous work related to the problem(s)
- reference list.

The proposal is submitted (with the supervisor's consent) to the Math DPC by the end of April. If there are objections and/or recommendations, the student has the right to re-submit an improved version of her/his proposal only once, in two weeks. Once it is approved by the Math DPC, the student receives 4 credits.

Credits to be earned in the first year:

Coursework	18 credits for grade
PhD Student Seminar	2+2 (research) credits (Pass/Fail)
Dissertation Proposal	4 (research) credits (Pass/Fail)
Altogether	26 credits

The Grade Point Average (GPA) is calculated from the grades earned for coursework. A student with  $GPA < 3.00$  cannot go to the Comprehensive Examination (see below). In order to qualify for the Comprehensive Exam, a probationary PhD student has to earn at least 18 course credits, plus 4 research credits for participation in the PhD Student Seminar, and have a 3.00 or higher GPA. Otherwise, her/his student status is terminated.

### *Comprehensive Examination*

This is a *written exam* which is usually taken on the week of May 15, and consists of a couple of theoretical questions and/or problems related to the material of three of the mandatory courses (i.e., *Topics in Algebra*, *Topics in Analysis*, *Topics in Combinatorics*, and *Topics in Topology and Geometry*), as specified in the syllabi of these courses. The three mandatory courses include *Topics in Algebra* and *Topics in Analysis*, and each student chooses between *Topics in Combinatorics* and *Topics in Topology and Geometry*. The grade of Comprehensive exam is the average of the three grades from the three subjects, and minimum passing grade for the Comprehensive exam is B+ (worth 3.33).

Students may retake the Comprehensive exam only once, before the candidacy examination (see below). Failure to pass the comprehensive exam even the second time automatically terminates the student's participation in the program.

### *Candidacy Examination*

If a student successfully passes the comprehensive exam and earns 4 (research) credits for the Dissertation Proposal (see above), then s/he is entitled to take the Candidacy Exam. This is a Pass/Fail *oral exam* which is usually taken on June 30 or before, after passing the comprehensive. It is given in the area in which the student has chosen to write the PhD dissertation. Good general knowledge of the specific area is also expected. In particular the student should be able to answer questions related to her/his Dissertation Proposal.

The exam committee, approved by the Math DPC, has three members, including the advisor, and the chair is different from the advisor. The material of the Candidacy Exam is worked out by the advisor, submitted to the Head, and approved by the Math DPC. The student receives the approved topics of the exam at least three weeks before the exam. The examiners receive both the exam's material and Dissertation Proposal. On this examination the student should demonstrate depth and breadth of knowledge as well as maturity and real mastery of basic material and the ability to apply it to specific problems.

The exam starts with 15-20 minutes oral presentation of the student on the prescribed topics, which is followed by questions by the examiners.

After a student passes the Candidacy Exam, s/he has the status of Doctoral (PhD) Candidate. In case of failure, the student may retake the Candidacy exam once by August 31 of the same year, possibly in another subject. Failure to pass this exam by August 31 automatically terminates the student's participation in the program.

### **Candidacy Period**

of a student starts when s/he passes the Candidacy Exam. Therefore this period starts from the second year of studies. With a prior approval of the Math DPC, a Doctoral Candidate may spend specified periods of time for a scientific trip away from Budapest, if this helps the student progress toward the PhD. The leader of the PhD student seminar is informed by the Head about the travel. The permission may be given for maximum one year, preferably in the third year of study, subject to the prior supervisor's agreement.

Doctoral Candidates provide a written report to the Math DPC at the end of each Academic Year of their study, documenting the progress of the work/research as agreed with the principal supervisor.

*Credits to be earned during the Second and Third Year*

During the Second Year, Doctoral Candidates are required to complete their course work by earning additional course credits, until they reach a total of 36 course credits for grade, and also by taking some additional courses for audit (worth 6 credits in total).

In the Second and the Third Year, students should primarily do research, under close supervision, towards the PhD dissertation. In particular, they are required to meet regularly their supervisors for consultation (for which each student earns 18 research credits/AY for a Pass/Fail qualification). For these credits, the supervisor may ask the student to attend certain research seminars and give talks. Participation in workshops and conferences is also taken into account.

Summarizing, each Doctoral Candidate has to earn  $2(2+2+18) = 44$  research credits during the second and the third academic year.

Credits to be earned in the Second and Third year:

Coursework	18 credits for grade (or as much is left to have 36 credits in total)
PhD Student Seminar	4+4 (research) credits (Pass/Fail)
Supervised Research	18+18 (research) credits (Pass/Fail)
Altogether	62 credits (or as much is left to have 88 credits in total)

**Extracurricular activity for 2 credits**

Each Doctoral Candidate is expected to earn 2 credits for a one semester long extracurricular activity from the list below during the first three years of study.

- tutoring at CEU or at Budapest Semester in Mathematics
- teaching a course at a university
- maintaining departmental website
- substantial help in organizing academic departmental activities like colloquium lectures or conferences

The 2 credits for these activities are awarded by the Doctoral Program Committee.

*Master of Philosophy (MPhil)*

If the doctoral student completes of all the above requirements except for the dissertation, and does not wish to write a thesis, then the Math DPC will recommend the candidate to be awarded the M. Phil. Degree in Mathematics and its Applications.

Award of MPhil means automatic termination of the student's enrollment in the doctoral program. If the student awarded an MPhil subsequently submits his or her dissertation and receives a PhD in the same program, his/her MPhil degree is revoked (as only one degree can be awarded for the same curriculum).

### *Dissertation Writing and Defense*

To award the PhD to a Doctoral Candidate, the only requirements are the credits to be earned as described above, and the successful defense of the dissertation.

Ideally a Doctoral Candidate writes her/his PhD dissertation within 3 years from the date of enrollment. However, the duration of PhD studies may be extended up to 6 years (or even more in exceptional cases). The Candidacy Period terminates when the dissertation is successfully defended (see below Section **Dissertation**).

## **Supervision**

Soon after enrollment, the Math DPC appoints an *advisor (early supervisor)* to each new student, in order to provide early supervision and counseling. Later, as students' interests get more specific, then either their advisors become *supervisors* or other (eligible) faculty members, closer to their interests, are appointed as supervisors by the Math DPC. Upon appointment, the names of supervisors are forwarded to the University Doctoral Committee for approval. Usually, the student's choice is honored, provided that the corresponding faculty member is willing to serve as supervisor.

A PhD student becomes a Doctoral (PhD) Candidate by the end of the first year, after passing the Candidacy Exam. This is the formal start of the *research period* of the candidate. However, each candidate is encouraged to start working on research topics earlier, as soon as possible after enrollment.

CEU encourages its Doctoral Candidates to spend time at another university during their candidacy period. Supervisors, in consultation with the Math DPC, will help to identify contact scholars in the host institutions who would be ready to serve as *external supervisors* for such Doctoral Candidates during their *research period abroad*.

Where it can be reasonably assumed that the supervisor may not be available for consultation for enough time or the studied field requires it, an *associate supervisor* should be appointed. The associate supervisor might be suggested by either the supervisor, or the Doctoral Candidate, and has to be approved by the Math DPC. A Doctoral Candidate may request the change of her/his supervisor or associate supervisor, if such a request is well motivated.

For detailed responsibilities of supervisors and PhD students, please visit:  
<http://www.ceu.hu/node/5360/572>, Section **CEU Doctoral Regulations**.

## Dissertation

### Dissertation Submission and Format

A Doctoral Candidate is required to submit her/his dissertation. There is a possibility of extending the length of the studies in cases of serious and unforeseeable interference with their studies (for example for medical reasons or unexpected changes in family circumstances). In case a foreseeable event prevents the student from making reasonable progress, he or she is advised to apply for a temporary withdrawal from the program.

Up to two months, the extensions can be granted by the Doctoral Program Committee. Beyond that period, extension can be granted by the University Doctoral Committee. The maximum time that can be granted beyond the regular enrolment is 2 years. Students need to apply for an extension at least two months before their enrolment expires, stating clearly the reason for the extension and its requested length. A request for extension always has to be supported by the student's supervisor.

During the period in which the student receives the stipend, s/he can request to have the stipend transfer stopped for a certain period of time, while remaining enrolled in the program. Requests must be submitted to the Doctoral Program Committee, with adequate supporting reasons for the request and a clear indication of the period for which the stipend is to be stopped (dd/mm/yy – dd/mm/yy). The transfer of the remaining part of the stipend will be resumed once this period expires.

The dissertation should be submitted with the approval (written report) of the supervisor(s). The report(s) of the supervisor(s), submitted to the Math DPC, must describe the candidate's evolution and main achievements, including the original results of the dissertation, specifying precisely that "*the dissertation can be submitted for defense.*"

The submitted dissertation shall include:

1. title page including the authors name, date of submission, supervisor's name;
2. table of contents;
3. abstract of maximum 500 words;
4. signed statement that the dissertation contains no materials accepted for any other degrees in any other institutions;
5. signed statement that the dissertation contains no materials previously written and/or published by another person, except where appropriate acknowledgment is made in the form of bibliographical reference, etc.;
6. where the work is based on joint research, disclosure of the respective contribution of the authors.

When submitting the dissertation for defense, the student has to attach the signed "Statement of objection" (see the Appendices of the CEU Doctoral Regulations).

### Dissertation Committee

Upon the submission of a PhD dissertation, the Math DPC recommends a Dissertation Committee (DC) to the University Doctoral Committee for approval. The DC has the following members: the chair of the Committee, the supervisor, the associate supervisor (if appointed), and at least two examiners. The chair of the DC is a CEU faculty, other than the supervisor(s) and examiners. The supervisor does not vote, and at least one third of the voting members of the DC at the defense must not be a CEU faculty, or a member of the Renyi Institute who had taught any CEU courses in the two Academic years preceding the defense. The examiners are asked to provide written reports on the thesis, within two months (during term time) of their appointment.

### **Dissertation Examination**

The dissertation is defended in the form of public oral defense.

Each examiner is asked to indicate in her/his report whether the dissertation can or cannot be submitted for defense. More precisely, each report can result in three possible outcomes: acceptance, conditional acceptance (i.e., some modifications are required), or rejection. In case one of the reports is negative (i.e., the examiner recommends rejection), a further examiner shall be appointed. If the majority of the examiners' reports is negative, the dissertation is regarded as failed, and the student status of the candidate is terminated, without the possibility of re-submission. Upon receiving all examiners' reports, if the majority of them is positive, the oral defense is scheduled within three months. The PhD candidate receives the reports in advance, and prepares written responses for the oral defense.

All the members of the DC are expected to attend the oral defense. Exceptionally, one of the examiners is allowed to be absent, but either s/he should be part of the defense live via internet, or the one third rule for the external voting members has to be fulfilled by the members of the DC present.

The usual procedure of the oral defense is the following:

The Chair introduces the Candidate as well as the members of the DC;

The Chair asks the department coordinator, or her/his representative, to keep the minutes of the proceedings, which in the end must be signed by all the present members of the DC;

The Chair invites the Candidate to summarize the main points of the dissertation;

The Chair invites the supervisor(s) to read out or summarize her/his (their) written report(s) (see above Section **Dissertation Submission and Format**);

The examiners read out or summarize their reports. In the case one of the external examiners is not present, the Chair reads out or summarizes her/his report;

The Chair invites the Candidate to read out her/his previously prepared responses to the comments and the criticism in the examiners' reports;

The Chair invites the members of the DC to make comments about the dissertation and the Candidate's responses to the critique, and ask further questions;

After the Candidate responds to these questions and comments, the Chair invites the public to ask questions or make comments on the dissertation;

The Candidate answers all possible questions from the floor;

Thereafter, the Chair invites the DC to retire behind closed doors to decide about the acceptance of the dissertation and the oral performance;

The Chair announces the decision of the DC.

The DC has to decide by simple majority vote between four options:

- a) candidate be awarded the degree without further modifications in the dissertation;
- b) candidate be awarded the degree subject to some modifications in the dissertation;
- c) candidate not yet be awarded the degree but permitted to re-submit the dissertation in a revised form;
- d) candidate not be awarded the degree.

In case b) is chosen, the DC has to decide which modifications are needed and which members of the DC will check whether the appropriate modifications are carried out. In this case, no further examination is needed.

In case c) (possibility to resubmit) is chosen, it is at the discretion of the DC to give further guidance (i.e., other than provided in the examiners' reports and during the oral defense) for improvement of the dissertation. Another examination is organized upon re-submission. Re-submission of the dissertation should take place within 2 years of the first defense.

In the case of a high quality thesis, the DC may award, in addition to the PhD, one of the following grades:

1. *Cum laude*, if the dissertation contains original results which demonstrate the author's ability to conduct scientific research.
2. *Magna cum laude*, if the dissertation contains notable results which could be published in international peer reviewed journals.
3. *Summa cum laude*, if in addition the dissertation makes decent progress on significant mathematical problems or applications.

Otherwise the grade *rite* will be assigned.

The decisions regarding the dissertation are based on the majority voting principle. If the DC cannot reach a majority decision, the Math DPC shall appoint two additional DC members within 15 days. The one third rule for the external voting members still has to be fulfilled. The enlarged DC shall make a decision by way of a simple majority of its members, without conducting another oral defense.

Minor formal corrections suggested by the examiners need not be expressly stipulated.

## **Appeals**

Students can lodge an appeal against any decision made by the Doctoral Program Committee or one of the Examination Committees to the University Doctoral Committee. These include decisions concerning withdrawal, re-enrolment and termination of student status, and decisions concerning the outcome of the Comprehensive and the Dissertation Examination. Any other grievances should be addressed to the Disciplinary or the Grievance Committee, according to the rules specified in the CEU Code of Ethics.

The appeal must be in writing and include the grounds for the appeal, and the desired outcome of the appeal. The appeal should be addressed to the Chair of the University Doctoral Committee, and sent within two weeks of the communication of the decision to the student.

## **Courses**

The Math PhD program offers courses in several fields in mathematics. Besides taking the mandatory courses (see Annex 1 for the list, and the attached file for the description of the courses), students choose elective courses from the attached file. Further elective courses may be added to the list, depending on the specific interests of the students.

### **Grading criteria for the courses**

- problem solving skills
- understanding and being able to apply the theory
- understanding the fundamental questions in the field of the course



## ANNEX 1

### **Mandatory Courses (taken in the first AY)**

M1. Topics in Algebra (*Fall term*)

M2. Topics in Analysis (*Fall term*)

M3. Topics in Combinatorics (*Winter term*)

M4. Topics in Topology and Geometry (*Winter term*)

## ANNEX 2 (Prerequisites for the Entrance Exam)

### Algebra

#### *Linear Algebra:*

- Vector spaces over  $\mathbf{R}$ ,  $\mathbf{C}$ , and other fields: subspaces, linear independence, basis and dimension.
- Linear transformations and matrices: constructing matrices of abstract linear transformations, similarity, change of basis, trace, determinants, kernel, image, dimension theorems, rank; application to systems of linear equations.
- Eigenvalues and eigenvectors: computation, diagonalization, characteristic and minimal polynomials, invariance of trace and determinant.
- Inner product spaces: real and Hermitian inner products, orthonormal bases, Gram-Schmidt orthogonalization, orthogonal and unitary transformations, symmetric and Hermitian matrices, quadratic forms.

#### *Abstract Algebra:*

- Groups: finite groups, matrix groups, symmetry groups, examples of groups (symmetric, alternating, dihedral), normal subgroups and quotient groups, homomorphisms, Sylow theorems.
- Rings: ring of integers, induction and well ordering, polynomial rings, roots and irreducibility, unique factorization of integers and polynomials, homomorphisms, ideals, principal ideals, Euclidean domains, prime and maximal ideals, quotients, fraction fields, finite fields.

### Analysis

- Real numbers as a complete ordered field. Extended real number system. Topological concepts: neighborhood, interior point, accumulation point, etc.
- Sequences of real numbers. Convergent sequences. Subsequences. Fundamental results.
- Numerical series. Standard tests for convergence and divergence.
- Real functions of one real variable. Limits, continuity, uniform continuity, differentiation, Riemann integration, fundamental theorem of calculus, mean value theorem, L'Hopital's rule, Taylor's theorem, etc. Sequences and series of functions. Pointwise and uniform convergence. Fundamental results. Power series and radii of convergence.
- The topology of  $\mathbf{R}^k$ . Connected and convex subsets of  $\mathbf{R}^k$ .
- Functions of several real variables. Limits, continuity, uniform continuity. Continuous functions on compact or connected sets. Partial derivatives. Differentiable functions. Taylor's theorem. Maxima and minima. Implicit and inverse function theorems.
- Multiple integrals. Integrals in various coordinate systems. Vector fields in Euclidean space (divergence, curl, conservative fields), line and surface integrals, vector calculus (Green's theorem in the plane, the divergence theorem in 3-space).
- Ordinary differential equations. Elementary techniques for solving special differential equations (separable, homogeneous, first order linear, Bernoulli's, exact, etc.). Existence and uniqueness of solutions to initial value problems (Picard's theorem). Linear differential equations and systems. Fundamental results.