Area COMPUTER SCIENCE

Study Program P4I1A Theoretical Computer Science and Artificial Intelligence

Subject Area Board

The current board make up is available at `http://mff.cuni.cz/phd/or/p4i1` .

Affiliated Institutions

- Institute of Mathematics of the Czech Academy of Sciences
  Žitná 25, 115 67 Praha 1
  `http://www.math.cas.cz`

- Institute of Computer Science of the Czech Academy of Sciences
  Pod vodárenskou věží 2, 182 07 Praha 8
  `http://www.cs.cas.cz/`

- Institute of Information Theory and Automation of the Czech Academy of Sciences
  Pod vodárenskou věží 4/1143, 182 08 Praha 8
  `http://www.utia.cas.cz/`

Thesis Topic

Thesis topics are listed in SIS at `http://mff.cuni.cz/phd/temata/p4i1` .

Available Courses

Code	Subject	Winter	Summer
NTIN091	**Seminar for MSc. and Ph.D.-students 1**	0/2 C	—
NTIN092	**Seminar for MSc. and Ph.D.-students 2**	—	0/2 C
NTIN088	**Algorithmic Randomness**	—	2/0 Ex
NDMI018	**Approximation and Online Algorithms**	—	2/2 C+Ex
NTIN017	**Parallel Algorithms**	—	2/0 Ex
NDMI025	**Randomized Algorithms**	—	2/2 C+Ex
NTIN097	**Hypercube structures**	2/0 Ex	—
NTIN096	**Pseudo-Boolean Optimization**	—	2/0 Ex
NTIN050	**Seminar on Computational Complexity**	0/2 C	0/2 C
NDBI031	**Statistical Methods in Data Mining Systems**	1/1 C+Ex	—

NTIN081	**Computational complexity and interactive protocols**	—	2/0 Ex
NTIN085	**Selected Topics in Computational Complexity I**	2/1 C+Ex	—
NTIN086	**Selected Topics in Computational Complexity II**	—	2/1 C+Ex
NTIN082	**Nonuniform computational models**	—	2/0 Ex
NAIL013	**Applications of Neural Networks Theory**	—	2/0 Ex
NAIL021	**Boolean Functions and Their Applications**	2/0 Ex	—
NAIL025	**Evolutionary Algorithms 1**	2/2 C+Ex	—
NAIL086	**Evolutionary Algorithms 2**	—	2/2 C+Ex
NAIL078	**Lambda Calculus and Functional Programming 1**	2/1 C+Ex	—
NAIL079	**Lambda Calculus and Functional Programming 2**	—	2/1 C+Ex
NAIL076	**Logic Programming 1**	2/0 Ex	—
NAIL077	**Logic Programming 2**	—	2/0 Ex
NAIL002	**Neural Networks**	4/2 C+Ex	—
NAIL071	**Planning and Scheduling**	—	2/0 Ex
NOPT042	**Constraint Programming**	2/2 C+Ex	—
NAIL031	**Representations of Boolean Functions**	—	2/0 Ex
NAIL029	**Machine Learning**	—	2/0 Ex

State Exam Requirements

State Exam consists of four questions. From each topic 1 and 2, the student will get one question. The third question is: for students of specialization Theoretical Computer Science from topics 3 or 4 (based on student selection), for students of specialization Artificial Intelligence from topics 5-7 (based on student selection). The fourth question is from the area selected by the supervisor (it could be one of the remaining topics):

1. Logic

Propositional and predicate logic, syntax and semantics, their relation. Formal proof systems, formal arithmetic, consistency and completeness, Gödel's theorems. Turing machines. Algorithmically undecidable problems, undecidability of predicate logic, undecidability of consistent extensions of elementary arithmetic. Undefinability of truth in arithmetic. The recursion theorems.

2. Complexity theory

Models of sequential and parallel computers. Boolean formulas and circuits. Complexity measures (time and space). Nondeterministic, alternating, and interactive computations. Complexity classes, reductions and complete problems, polynomial hierarchy. Basic concepts of proof complexity. Lower bounds for random and explicit functions. Randomized algorithms and pseudorandomness. Communication complexity and its applications. Basics of theoretical cryptography. Quantum circuits and algorithms.

3. Data Structures

Computational models (RAM and its variants). Data compression. Search trees. Hashing. Advanced heaps. Data structures for integers. Data structures for storing

strings. Multi-dimensional data structures. Data structures for graphs. Dynamization and persistence. Memory hierarchy. Data stream problems.

4. Algorithms

Deterministic, randomized, and parallel algorithms. Design and analysis of efficient algorithms. Graph algorithms. Efficient algorithms for linear programming and their applications. Methods for solving hard problems: Approximation algorithms, approximation schemes, heuristic techniques. Basic cryptographic protocols.

5. Artificial Intelligence

Knowledge representation, automated theorem proving, resolution. Boolean satisfiability, constraint satisfaction. Declarative programming languages. State-space search techniques, meta-heuristics, their examples, and applications, local search. Action planning. Uncertainty reasoning, Bayesian networks, Markov Decision Processes. Multiagent systems and game theory.

6. Machine Learning and Data Analysis

Theoretical aspects of machine learning. Types of models: complexity penalty, kernel methods, systems of basis functions. Probabilistic approaches. Machine learning algorithms. Reinforcement learning. Artificial neural networks, their training, application, and characteristic properties. Data mining methods. Representation, evaluation, and visualization of the obtained knowledge.

7. Nature-Inspired Optimization Algorithms

Evolutionary algorithms, representations of the individual, genetic operators, parameters adaptation and self-adaptation, constraint handling. Evolutionary strategies. Multi-objective evolutionary algorithms. Tree-based, linear, and Cartesian genetic programming, grammatical evolution. Application of evolutionary computing – combinatorial optimization, continuous optimization, neuroevolution, and rule-based systems. Co-evolution and meta-evolution. Particle swarm optimization, ant colony optimization and their applications.

Recommended literature

1. Logic:

Nerode A., Shore R. A.: **Logic for Applications.** *2nd ed., Springer, 1997.*

Pudlák P.: **Logical Foundations of Mathematics and Computational Complexity - A Gentle Introduction.** *Springer, 2013.*

Rautenberg W.: **A concise introduction to mathematical logic.** *Springer, 2010.*

Soare, R.I.: **Turing Computability, Theory and Applications.** *Springer, 2016.*

2. Complexity Theory:

Arora, S., Barak, B.: **Computational Complexity: A Modern Approach.** *Text přístupný na* `http://theory.cs.princeton.edu/complexity/` .

Kushilevitz, E., Nisan, N.: **Communication complexity.** *Cambridge University Press, Cambridge, 1997.*

Papadimitriou, C. H.: **Computational Complexity.** *Addison–Wesley, Reading, MA, 1994.*

Jukna S.: **Boolean Function Complexity: Advances and Frontiers.** *Springer–Verlag, 2012.*
Cover T.M., Thomas, J.A.: **Elements of Information Theory.** *John Wiley & Sons, 2nd edition, 2006.*

3. Data Structures:

Navarro, G.: **Compact Data Structures: A Practical Approach.** *Cambridge University Press, 2016.*
Crochemore, M., Hancart, Ch., Lecroq. T.: **Algorithms on Strings.** *Cambridge University Press, 2014.*
Navarro, G., Raffinot. M.: **Flexible Pattern Matching in Strings: Practical On-Line Search Algorithms for Texts and Biological Sequences.** *Cambridge University Press, 2002.*
Mehta, D.P., Sahni, S.: **Handbook of Data Structures and Applications.** *Chapman Hall/CRC Computer and Information Science Series, 2004.*
Chakrabarti, A.: **Data Stream Algorithms, Lecture Notes,** *by Dartmouth College, 2014.*

4. Algorithms:

Cormen et al: **Introduction to Algorithms.** *3rd ed., MIT press, 2009.*
Kleinberg, J., Tardos, E.: **Algorithms Design.** *Addison–Wesley, Reading, MA, 2005.*
Vazirani, V. V.: **Approximation Algorithms.** *Springer–Verlag, 2001.*
Williamson, D. P., Shmoys, D. B.: **The Design of Approximation Algorithms.** *Cambridge University Press, 2011.*
Mitzenmacher, M., Upfal, E.: **Probability and Computing: Randomized Algorithms and Probabilistic Analysis.** *Cambridge Univeristy Press, 2005.*

5. Artificial Intelligence:

Russell, S. J., Norvig, P.: **Artificial Intelligence: A Modern Approach.** *3rd ed., Pearson, 2009.*
Ghallab, M., Nau, D., Traverso, P.: **Automated Planning: Theory and Practice.** *Morgan Kaufmann, 2004.*
Rossi, F., Beek van, P., Walsh, T. (eds.): **Handbook of Constraint Programming.** *Elsevier, 2006.*
Dechter, R.: **Constraint Processing.** *Morgan Kaufmann, 2003.*

6. Machine Learning and Data Analysis:

Aggarwal, C. C.: **Data Mining: The Textbook.** *Springer–Verlag, 2015.*
Goodfellow, I., Bengo, Y., Courville, A.: **Deep Learning.** *The MIT Press, 2016.*
Hastie, T., Tibshirani, R., Friedman, J.: **The Elements of Statistical Learning.** *Springer, 2013.*
James, G., Witten, D., Hastie, T., Tibshirani, R.: **An Introduction to Statistical Learning with Applications in R.** *Springer, 2013.*
Marsland, S.: **Machine Learning: An Algorithmic Perspective.** *2nd ed., Taylor Francis, 2015.*

7. Nature-Inspired Optimization Algorithms:

Eiben, A. E., Smith, J. E.: **Introduction to Evolutionary Computing.** *2nd ed., Springer, 2015.*
Michalewicz. Z., Fogel, D.B.: **How to Solve It: Modern Heuristics.** *2nd ed., Springer, 2004.*
Poli R., Langdon. W.B., McPhee. N.F.: **Field Guide to Genetic Programming.** *Lulu, 2008.*
Yang, X.-S.: **Nature-Inspired Optimization Algorithms.** *Elsevier, 2014.*
Ryan C., O'Neill, M., Collins, J.J. (Eds): **Handbook of Grammatical Evolution.** *Springer, 2018.*

Study Program P4I2A Computer Science - Software Systems

Subject Area Board

The current board make up is available at `http://mff.cuni.cz/phd/or/p4i2` .

Thesis Topics

Thesis topics are listed in SIS at `http://mff.cuni.cz/phd/temata/p4i2` .

Available Courses

Code	Subject	Winter	Summer
NSWI026	**Advanced aspects of software engineering**	—	2/2 C+Ex
NPRG058	**Advanced Programming in Parallel Environment**	2/2 C+Ex	—
NSWI057	**Advanced topics in distributed and component-based systems I**	0/2 C	—
NSWI058	**Advanced topics in distributed and component-based systems II**	—	0/2 C
NSWI104	**Company Management – System Dynamics II**	—	0/2 C
NPRG014	**Concepts of Modern Programming Languages**	0/3 C	—
NDBI042	**Data Visualization Techniques**	—	2/1 C+Ex
NAIL094	**Decision procedures and SAT/SMT solvers**	—	2/2 C+Ex
NTIN033	**Experimental Analysis of Algorithms**	—	2/2 C+Ex
NTIN043	**Formal Foundations of Software Engineering**	2/2 C+Ex	—
NMAI061	**Methods of Mathematical Statistics**	—	2/1 C+Ex
NSWI080	**Middleware**	—	2/1 MC
NSWI164	**Model-driven Development**	0/1 C	—

NSWI029	**Modern Trends in Computer Science**	0/2 C	0/2 C
NDBI033	**Non-traditional Database Models, Architectures and Languages**	2/0 Ex	—
NTIN018	**Probabilistic Analysis of Algorithms**	2/0 Ex	—
NMAI060	**Probabilistic Methods**	2/0 Ex	—
NSWI132	**Program Analysis and Code Verification**	—	2/2 C+Ex
NSWI103	**Project Management – System Dynamics I**	0/2 C	—
NSWI063	**Start-up or corporation: Introduction to a career in IT**	0/1 C	—
NDBI019	**Stochastic Methods in Databases**	—	2/0 Ex
NSWI101	**System Behaviour Models and Verification**	2/2 C+Ex	—
NDBI016	**Transactions**	—	2/0 Ex

State Exam Requirements

The exam deals with three topic areas. The first topic area is that of the dissertation, the other two areas are selected from the list of topic areas by the student in cooperation with the advisor. In all three areas, the exam consists of a student presentation followed by a discussion with the exam board. The board evaluates in particular the dissertation perspective and the familiarity of the student with the selected areas in connection to the overall study topic.

For the first topic area (the dissertation topic), the presentation should explain the planned contribution of the dissertation in the context of the state-of-the-art research, including current results and future research plans, so that the board can form an accurate opinion on the future shape of the thesis, the methods used and the results expected.

For the other two topic areas (the elective topics), the presentation should critically summarize the topic area, particularly in connection with the overall study topic of the student. The board expects a choice of current and relevant research topics, possibly including relevant theoretical background. The advisor is responsible for proposing extensions to the topic area list or updates to the list of research resources, to be approved by the subject area board prior to the exam, so that the list includes content relevant to the overall study topics of the student. Each topic area should be defined as a compact list of research resources (especially research publications) that correspond to the state-of-the-art and the exam requirements.

Distributed and Edge Cloud Systems

M. Satyanarayanan: **The Emergence of Edge Computing** *IEEE Computer, 2017.*

M. Villari, M. Fazio, S. Dustdar, O. Rana, R. Ranjan: **Osmotic Computing: A New Paradigm for Edge/Cloud Integration.** *IEEE Cloud Computing, 2016.*

G. Coulouris, J. Dollimore, T. Kindberg, G. Blair: **Distributed Systems: Concepts and Design (5th Edition)** *Pearson, 2011.*

Modeling Multi-Model Data

A. Hernández et al.: **Exploring the visualization of schemas for aggregate-oriented NoSQL databases.** *Proc. ER Forum 2017.*

M.-A. Baazizi et al.: **Parametric schema inference for massive JSON datasets.** *The VLDB Journal, 2019.*

M. Klettke, U. Storl, S. Scherzinger: **Schema extraction and structural outlier detection for JSON-based NoSQL data stores.** *Proc. BTW 2015.*

A. A. Frozza, E. D. Defreyn, R. Dos Santos Mello: **A Process for Inference of Columnar NoSQL Database Schemas.** *Proc. SBC 2020.*

P. Atzeni et al.: **Data modeling in the NoSQL world.** *Computer Standards Interfaces, 2020.*

D. I. Spivak: **Functorial data migration.** *Information and Computation, 2012.*

J. Shinavier, R. Wisnesky: **Algebraic property graphs.** *arXiv 1909.04881, 2019.*

Z. H. Liu et al.: **Multi-model database management systems-a look forward.** *Springer, 2018.*

Modern Database Systems

P. J. Sadalage, M. Fowler: **NoSQL distilled: a brief guide to the emerging world of polyglot persistence.** *Pearson Education, 2013.*

I. Holubová et al.: **Big Data a NoSQL databáze.** *Grada, 2015.*

J. Lu, I. Holubová: **Multi-model databases: a new journey to handle the variety of data.** *ACM Computing Surveys, 2019.*

Object Oriented Systems

A. Rausch et al.: **The Common Component Modeling Example: Comparing Software Component Models.** *Springer, 2008.*

B. Pierce: **Types and Programming Languages.** *MIT Press, 2002.*

D. Flanagan: **JavaScript: The Definitive Guide.** *O'Reilly Media, 2011.*

D. Ghosh: **DSLs in Action.** *Manning Publications, 2010.*

D. Koenig, A. Glover, P. King, G. Laforge, J. Skeet: **Groovy in Action.** *Manning Publications, 2007.*

G. T. Brown: **Ruby Best Practices.** *O'Reilly Media, 2009.*

G. T. Leavens, M. Sitaraman: **Foundations of Component–Based Systems.** *Cambridge University Press, 2000.*

M. Abadi, L. Cardelli: **A Theory of Objects.** *Springer, 1998.*

M. Fogus, C. Houser: **Joy of Closure.** *Manning Publications, 2011.*

M. Odersky, L. Spoon, B. Venners: **Programming in Scala (2nd Edition).** *Artima, 2010.*

R. Miles: **AspectJ Cookbook.** *O'Reilly, 2004.*

T. Stahl, M. Volter: **Model–Driven Software Development.** *Wiley, 2006.*

Compilers

A. V. Aho, M. S. Lam, R. Sethi, J. D. Ullman: **Compilers: Principles, Techniques, and Tools (2nd Edition).** *Addison Wesley, 2006.*

C. F. Bolz, A. Cuni, M. Fijałkowski, A. Rigo: **Tracing the Meta-Level: PyPy's Tracing JIT Compiler.** *Proc. OOPSLA, 2009.*

D. Grune, H. E. Bal, C. J. H. Jacobs, K. G. Langendoen: **Modern Compiler Design.** *J. Wiley, 2000.*

D. Grune, K. van Reeuwijk, H. Bal, C. J. H. Jacobs, K. G. Langendoen: **Modern Compiler Design.** *Springer, 2012.*

J. P. Shen, M. H. Lipasti: **Modern Processor Design: Fundamentals of Superscalar Processors.** *Waveland Press, 2013.*
M. Arnold, S. Fink, D. Grove, M. Hind, P. F. Sweeney: **Architecture and Policy for Adaptive Optimization in Virtual Machines.** *IBM, 2004.*
R. Allen, K. Kennedy: **Optimizing Compilers for Modern Architectures: A Dependence–Based Approach.** *Morgan Kaufmann, 2001.*

Software System Behavior Specification

A. R. Bradley, Z. Manna: **The Calculus of Computation.** *Springer, 2007.*
E. A. Emerson: **Temporal and Modal Logic.** *Elsevier, 1990.*
E. M. Clarke, O. Grumberg, D. A. Peled: **Model Checking.** *The MIT Press, 1999.*
F. Nielson, H. R. Nielson, C. Hankin: **Principles of Program Analysis.** *Springer, 2004.*
J. A. Bergstra, A. Ponse, S. A. Smolka: **Handbook of Process Algebra.** *Elsevier, 2001.*
K. McMillan: **Symbolic Model–Checking.** *Kluwer, 1993.*
R. Milner: **Communication and Concurrency.** *Prentice Hall, 1995.*

Machine Learning

T. Hastie, R. Tibshirani, J. Friedman: **The Elements of Statistical Learning: Data Mining, Inference, and Prediction (2nd Edition).** *Springer, 2017.*
I. Goodfellow, Y. Bengio, A. Courville: **Deep Learning.** *MIT Press, 2016.*

Study Program P4I3A Computational Linguistics

Subject Area Board

The current board make up is available at `http://mff.cuni.cz/phd/or/p4i3` .

Thesis Topic

Thesis topics are listed in SIS at `http://mff.cuni.cz/phd/temata/p4i3` .

Available Courses

Code	Subject	Winter	Summer
NPFL004	**Seminar on Formal Linguistics**	0/2 C	0/2 C
NPFL006	**Introduction to Formal Linguistics**	2/0 Ex	—
NPFL015	**Methods of Automated Translation**	0/2 C	—
NPFL024	**Syntactic Parsing of Czech**	—	0/2 C
NPFL038	**Fundamentals of Speech Recognition and Generation**	2/2 C+Ex	—
NPFL054	**Introduction to Machine Learning with R**	—	2/2 C+Ex

NPFL063	**Introduction to General Linguistics**	2/1 C+Ex	—
NPFL067	**Statistical Methods in Natural Language Processing I**	2/2 C+Ex	—
NPFL068	**Statistical Methods in Natural Language Processing II**	—	2/2 C+Ex
NPFL070	**Language Data Resources**	1/2 MC	—
NPFL073	**Mathematical Methods in Linguistics**	0/2 C	—
NPFL075	**Dependency Grammars and Treebanks**	—	2/2 C+Ex
NPFL079	**Algorithms in Speech Recognition**	—	2/2 C+Ex
NPFL083	**Linguistic Theories and Grammar Formalisms**	—	2/2 C+Ex
NPFL087	**Statistical Machine Translation**	—	2/2 C+Ex
NPFL094	**Morphological and Syntactic Analysis**	2/0 MC	—
NPFL095	**Modern Methods in Computational Linguistics**	0/2 C	—
NPFL097	**Unsupervised Machine Learning in NLP**	1/1 C	—
NPFL099	**Statistical Dialogue Systems**	2/1 C+Ex	—
NPFL100	**Variability of Languages in Time and Space**	1/1 C	—
NPFL103	**Information Retrieval**	2/2 C+Ex	—
NPFL106	**Linguistics**	—	1/1 MC
NPFL109	**Digital Sound Processing**	—	2/2 C+Ex
NPFL114	**Deep Learning**	—	3/2 C+Ex
NPFL116	**Compendium of the Neural Machine Translation**	—	0/2 C
NPFL118	**Natural language processing on computational cluster**	0/2 C	—
NPFL120	**Multilingual Natural Language Processing**	—	1/1 MC
NPFL122	**Deep Reinforcement Learning**	2/2 C+Ex	—
NPFL123	**Dialogue Systems**	—	2/2 C+Ex
NPFL124	**Natural Language Processing**	—	2/1 C+Ex
NPFL125	**Introduction to Language Technologies**	0/2 MC	—
NPFL129	**Introduction to Machine Learning with Python**	2/2 C+Ex	—

State Exam Requirements

The exam composes of two parts. In the first part, students summarize state of the art and present main outcomes of their own research related to the topics of their theses. In the second part, each student is examined on three exam topics. Topic 1 is obligatory, and then the student chooses two out of the remaining eight topics (any combination is possible).

Exam topic 1 - Common basics

Basic tasks and applications of Natural Language Processing. Basic notions in probability, language modeling. Basic notions in supervised and unsupervised ma-

chine learning. Computational model of artificial neural networks. Basic notions in graph theory. Automata, formal grammars, Chomsky hierarchy. Levels of language description. Basic notions in lexicology. Basic notions in language typology. Language corpora, basic types. Linguistic annotation principles. Morphological annotation. Syntactic annotation (constituency and dependency treebanks). Parallel corpora. Specialized corpora. Lexical resources (dictionaries, ontologies etc.). Basic principles of using data for experiment evaluation, basic evaluation measures, inter-annotator agreement. Search in language data.

Optional exam topics for the computational specialization

Exam topic 2 - Basic statistical and machine learning approaches to Natural Language Processing

Probabilistic Natural Language Processing. Language models, smoothing. Noisy channel model. Supervised machine learning (linear regression, logistic regression, decision trees, perceptron, Support Vector Machines, K nearest neighbors etc.). Kernel methods. Unsupervised machine learning (clustering, Expectation-Maximization). Hidden Markov Models (Baum-Welch, Forward-Backward, and Viterbi algorithms). Algorithms for statistical tagging. Algorithms for constituency and dependency statistical parsing. Statistical machine translation. Basic notions of neural networks in Natural Language Processing. Significance tests.

Exam topic 3 - Advanced Machine Learning

Training artificial neural networks (ANNs). Regularization methods for ANNs. Convolutional networks. Recurrent networks. Distributed representations and word embeddings. Architectures for natural language processing. Generative modeling of text and images. Reinforcement learning. Discrete latent variable optimization. Bayesian inference. Markov Chain Monte Carlo methods.

Exam topic 4 - Machine Translation

The task of machine translation (MT complexity, space of correct and incorrect translations, ambiguity and vagueness, document-level aspects). MT evaluation (manual, automatic; reference-based, reference-free). Data for machine translation (alignment of documents, sentences, words and other translation units). Classical statistical MT (phrase-based MT and other methods relying on translation units). Heuristic approaches (transfer-based MT, hybrid methods). Neural MT (architectures, relation between discrete and continuous representation of natural language expressions). Advanced methods (multi-task, multi-lingual MT, etc.). Formal description of natural languages for MT (morphology and syntax in MT). Computer-assisted translation (technologies, TM, incremental translation).

Exam topic 5 - Information Retrieval

Boolean model. Inverted index, index compression. Tolerant retrieval. Spelling correction. Vector space model. Evaluation and benchmarks. Relevance feedback, query expansion. Probabilistic models. Language models. Document classification. Learning to rank. Document clustering. Latent Semantic Indexing.

Exam topic 6 - Speech Processing and Dialogue Systems

Phonetic acoustic modelling. Baum-Welch and Viterbi algorithms for speech recognition. Adaptation techniques. Text-to-speech synthesis. Dialogue Systems.

Basic dialogue system components. Dialogue State, dialogue management. Language understanding. Response generation. Neural dialogue systems. Dialogue system evaluation.

Optional exam topics for the linguistic specialization

Exam topic 7 - Language System Formal Description

Basic notions in phonetics and phonology. Morphological structure of languages. Basic word-formation processes. Syntactic structure and its representation, surface-syntactic and deep-syntactic structure of sentence, role of valency, information structure. Language meaning, form-meaning asymmetry, language meaning vs. cognitive content. Text structure: interclausal relations, coreference and bridging anaphora. Basic notions in stylistics; basic styles and genres, language means in stylistics. Basic notions in semantics and pragmatics.

Exam topic 8 - Linguistic formalisms (basic characteristics)

Linguistic formalisms and their purpose. Functional Generative Description. Generative grammar, Government Binding, Minimalism. Grammar and lexicon (grammatical vs. lexical phenomena, boundary issues). Comparison of lexicalist and grammatically oriented approaches. Comparison of syntactic representation across linguistic formalisms. Verb as the core element of the sentence in different formalisms. Semantic representation in different linguistic approaches.

Exam topic 9 - Variability of languages and basic notions of language typology

Variability of languages and possible classifications (genetic, areal, typological). Genetic classification of languages, language families. Areal classification of languages, Sprachbunds. Phoneme inventories, distinctive features and suprasegmental phenomena from a contrastive perspective; International Phonetic Alphabet; syllable formation. Spoken vs. written language; types of writing systems. Morphological structure of languages (inflectional, agglutinative, isolating and polysynthetic types). Parts of speech and their comparability across languages. Word order from a contrastive perspective; free and fixed word order; dominant word order; correlations of word-order patterns. Word-formation processes across languages. Harmonization of annotation schemes.

Recommended literature

Exam topic 1 - Common basics

Manning C. D., Schuetze, H.: **Foundations of Statistical Natural Language Processing.***MIT Press, Cambridge, 1999.*

Lüdeling, A., Kytö, M.: **Corpus Linguistics: an International Handbook**, *Volume 1. W. de Gruyter, 2008*

Ide, N., Pustejovsky, J. (eds.): **Handbook of Linguistic Annotation.** *Springer, 2017.*

Exam topic 2 - Basic statistical and machine learning approaches to Natural Language Processing

Manning C. D., Schuetze, H.: **Foundations of Statistical Natural Language Processing.***MIT Press, Cambridge, 1999.*

Jurafsky, D. and J. H. Martin: **Speech and Language Processing.***Prentice-Hall, 2nd edition. 2009.*

Bishop, C.: **Pattern Recognition and Machine Learning.***Springer, 2007.*

Exam topic 3 - Advanced Machine Learning

Ian Goodfellow and Yoshua Bengio and Aaron Courville: **Deep Learning.***MIT Press, 2016.*

Richard, S. Sutton and Andrew G. Barto: **Reinforcement Learning: An Introduction (Second Edition).***MIT Press, Cambridge, MA, 2018.*

Murphy, K.: **Machine Learning: a Probabilistic Perspective.***MIT Press, 2012.*

Exam topic 4 - Machine Translation

Philipp Koehn: **Statistical Machine Translation.***Cambridge University Press New York, 2010*

Philip Williams, Rico Sennrich, Matt Post, Philipp Koehn: **Syntax-based Statistical Machine Translation**. *Morgan Claypool Publishers, 2016.*

Goldberg, Y.: **Neural Network Methods for Natural Language Processing.***Morgan Claypool Publishers, 2017*

Exam topic 5 - Information Retrieval

Christopher D. Manning, Prabhakar Raghavan, Hinrich Schütze: **Introduction to Information Retrieval**. *Cambridge University Press, 2008.*

Charu Aggarwal, Chengxiang Zhai: **Mining Text Data**. *Springer, 2012*

David A. Grossman, Ophir Frieder: **Information Retrieval, Algorithms and Heuristics**. *Springer, 2004.*

Exam topic 6 - Speech Processing and Dialogue Systems

Jurafsky, D. and J. H. Martin: **Speech and Language Processing.***Prentice-Hall, 2nd edition. 2009.*

Yu, D., Deng, L.: **Automatic Speech Recognition: A Deep Learning Approach.***Signals and Communication Technology, Springer London, 2014.*

Gao, J., Galley, M., Li, L.: **Neural Approaches to Conversational AI.***Foundations and Trends in Information Retrieval, Vol. 13, No. 2-3, pp 127-298. 2019.*

Exam topic 7 - Language System Formal Description

Booij, G.: **Morphology. An International Handbook on Inflection and Word-Formation.***Volume 1, de Gruyter, 2000.*

Ágel, V. et al. (eds.): **Dependency and Valency. An international Handbook of Contemporary Research.***Volume 1. de Gruyter, 2003.*

Cruse, D. A.: **Meaning in language: an introduction to semantics and pragmatics.***Oxford: Oxford University Press, 2011.*

Exam topic 8 - Linguistic formalisms (basic characteristics)

Allan, K. (ed.): **The Oxford Handbook of the History of Linguistics.***Oxford Univesity Press. 2013*

Ágel, V. et al. (eds.): **Dependency and Valency. An international Handbook of Contemporary Research.***Volume 1. de Gruyter, 2003.*

Exam topic 9 - Variability of languages and basic notions of language typology

Haspelmath, M. et al. (eds.): **Language typology and language universals.***De Gruyter, 2001.*

Comrie, B.: **Language universals and linguistic typology.***University of Chicago press, 1989.*

Study program P4I4A Computer Science - Theory of Computing, Discrete Models and Optimization

Subject Area Board

The current board make up is available at `http://mff.cuni.cz/phd/or/p4i4` .

Affiliated Institutions

- Institute of Mathematics of the Czech Academy of Sciences
  Žitná 25, 115 67 Praha 1
  `http://www.math.cas.cz`

Thesis Topics

Thesis topics are listed in SIS at `http://mff.cuni.cz/phd/temata/p4i4` .

Available Courses

Code	Subject	Winter	Summer
NDMI066	**Algebraic Number Theory and Combinatorics**	2/0 Ex	—
NDMI028	**Linear Algebra Applications in Combinatorics**	2/2 C+Ex	—
NDMI064	**Applied Discrete Mathematics**	2/0 Ex	—
NTIN103	**Introduction to Parameterized Algorithms**	2/2 C+Ex	—
NDMI009	**Introduction to Combinatorial and Computational Geometry**	2/2 C+Ex	—
NTIN022	**Probabilistic Techniques**	2/2 C+Ex	—
NDMI055	**Selected Chapters on Combinatorics 1**	2/0 Ex	—
NTIN085	**Selected Topics in Computational Complexity I**	2/1 C+Ex	—
NDMI045	**Analytic and Combinatorial Number Theory**	—	2/0 Ex
NDMI035	**Geometric Representations of Graphs 2**	—	2/0 Ex
NDMI078	**Graphs and counting**	—	2/0 Ex
NDMI013	**Combinatorial and Computational Geometry 2**	—	2/2 C+Ex
NDMI015	**Combinatorial Counting**	—	2/0 Ex
NMAI071	**Math++**	—	2/2 C+Ex
NDMI058	**Flows and Cycles in Graphs**	—	2/2 C+Ex
NDMI056	**Selected Chapters on Combinatorics 2**	—	2/0 Ex
NTIN086	**Selected Topics in Computational Complexity II**	—	2/1 C+Ex

NDMI090	**Bioinformatics seminar**	0/2 C	0/2 C
NDMI041	**Seminar on Combinatorics for Advanced Students**	0/3 C	0/3 C
NDMI070	**Selected Chapters on Graph Theory**	2/0 Ex	2/0 Ex

State Exam Requirements

The student chooses four of the mandatory topics, two of them from the topics 1.– 4. and two of them from the topics 5.– 12. After a consultation with the advisor, an elective topic will be chosen; one of the topics 5.– 12. can be used as the elective one.

The extent of the chosen topics must correspond to one of the comprehensive advanced texts from the recommended literature. However, with the agreement of the examiner, a more narrow in-depth subtopic can be chosen; in this case, the study texts (books or journal articles) are subject to approval by the subject area board.

1. Discrete Mathematics

Matchings, packings and coverings in graphs. Graph connectivity. Graph drawing and surfaces. Graph coloring and flows. Extremal and Ramsey graph theory. Hamiltonicity. Random graphs. Structural graph theory.

2. Logic

Model theory. Algebraic specification in software engineering. Propositional and predicate logic. Syntax and semantics. Formal systems. Consistency and completeness, Gödel's theorems.

3. Computational complexity

Basic complexity classes. Diagonalization. Polynomial hierarchy. Circuits. Randomness and derandomization. Interactive protocols. Lower bounds in various computational models. PCP theorem.

4. Design and analysis of algorithms

Matchings. Network flows. Shortest paths. Spanning trees. Matroid algorithms. Algorithms for planar graphs, applications of sublinear separators.

5. Combinatorial and continuous optimization

Polyhedral combinatorics. Linear programming and duality. Integer programming. Combinatorial optimization algoritms.

6. Combinatorics and algebraic combinatorics

Linear-algebraic methods, applications of eigenvalues. Graph polynomials. Symmetry and regularity. Matroid theory.

7. Theory of structures

Categories, functors. Factorization. Monads. Topological and algebraic categories. Categorical aspects of combinatorial objects.

8. Probabilistic method

Non-constructive methods in combinatorics. Expectation and moments. Local lemma. Concentration estimates. Random graphs. Geometric applications. Pseudorandomness.

9. Topological methods and discrete geometry

Equitable division. Borsuk-Ulam theorem. Applications in graph coloring. Embedding. Convex sets and polytopes. Envelopes. Transversals and epsilon-nets. Volume in high dimensions.

10. Cryptography

Computational complexity and one-way functions. Applications of the number theory. Pseudorandom generators. Zero Knowledge Proofs. Encryption and authentication protocols.

11. Data structures

Queues. Dictionaries. Higher-dimensional structures. Dynamic structures. Aplications.

12. Algorithmic game theory

Nash equilibrium. Two-player games. Combinatorial algorithms. Applications in cryptography and computational complexity. Combinatorial auctions.

Recommended literature

1. Discrete Mathematics

Diestel, R.: **Graph theory.** *Springer–Verlag 2010.*

Bollobás, B.: **Modern graph theory.** *Graduate Text in Mathematics 184, Springer–Verlag, New York, 1998.*

Hell, P., Nešetřil, J.: **Graphs and homomorphisms.** *Oxford University Press, Oxford, 2004.*

2. Logic

Abramsky, S., Gabbay, D.:**Handbook of Logic in Computer Science.** *Clarendon Press, Oxford, 1992.*

Shoenfield, J. R.: **Mathematical logic.** *Addison–Wesley, Reading, 1967.*

3. Computational complexity

Arora, S. and Barak, B.: **Computational Complexity: A Modern Approach**

Papadimitriou, C. H.: **Computational Complexity.** *Addison–Wesley, Reading, 1994.*

Garey, M. R., Johnson, D. S.: **Computers and Intractability, A guide to the theory of NP–completness.** *W. H. Freeman, San Francisco, 1979.*

Sipser, M.: **Introduction to the Theory of Computation.** *PWS Publishing Company, Boston, 1997.*

4. Design and analysis of algorithms

Kozen, D. C.: **The Design and Analysis of Algorithms.** *1992.*

Marek Cygan, Fedor V. Fomin, Lukasz Kowalik, Daniel Lokshtanov, Dániel Marx, Marcin Pilipczuk, Michal Pilipczuk, Saket Saurabh: **Parameterized Algorithms.** *Springer, 2015.*

Shmoys, D. B., Williamson, D. P.: **The Design of Approximation Algorithms.** *Cambridge University Press 2011.*

M. Mitzenmacher, E. Upfal: **Probability and Computing: Randomized Algorithms and Probabilistic Analysis.** *Cambridge Univ. Press, 2005.*

Knuth, Donald E.: **Art of Computer Programming, Volumes 1-4A.** *Addison-Wesley Professional, 2011.*

5. Combinatorial and continuous optimization

Cook, W. J., Cunnigham, W. H., Pulleyblank, W. R., Schrijver, A.: **Combinatorial optimization.** *Wiley, New York, 1998.*

Schrijver, A.: **Theory of linear and integer programming.** *Wiley, New York, 1998.*

Schrijver, A.: **Combinatorial Optimization, Polyhedra and Efficiency.** *Springer- Verlag 2003.*

6. Combinatorics and algebraic combinatorics

Biggs, N. L.: **Algebraic graph theory.** *Cambridge University Press, Cambridge 1994.*

Oxley, J.: **Matroid theory.** *Oxford University Press, Oxford, 1992.*

Graham, R. L., Spencer, J., Rothschild, B.: **Ramsey Theory.** *Wiley, New York, 1990.*

Nešetřil, J., Ossona de Mendez, P.: **Sparsity, Graphs, Structures, and Algorithms.**

Cvetkovic, D. M., Doob, M., Sachs, H.: **Spectra of graphs, Theory and applications.** *J. A. Barth Verlag, Leipzig, 1995.*

7. Theory of structures

Adámek, J., Herrlich, H., Strecker, G. E.: **Abstract and Concrete Categories.** *Wiley, New York, 1990.*

MacLane, S.: **Categories for the working mathematician.** *Graduate Texts in Mathematics 5, Springer–Verlag, New York, 1971.*

8. Probabilistic method

Alon, N., Spencer, J.: **The Probabilistic Method.** *Wiley, New York, 2000.*

Grimmet, G. R., Stirzaker, D. R.: **Probability and random processes: Problems and solutions.** *Claredon Press, Oxford, 1992.*

Motwani, R., Raghavan, P.: **Randomized algorithms.** *Cambridge University Press, Cambridge, 1995.*

9. Topological methods and discrete geometry

de Longueville, M.: **A Course in Topological Combinatorics.** *Springer 2013.*

Matoušek, J.: **Lectures on Discrete Geometry.** *Springer 2002.*

Kelly, J.: **General Topology.** *Van Nostrand, New York, 1955.*

Matoušek, J.: **Using the Borsuk-Ulam Theorem.** *Lectures on Topological Methods in Combinatorics and Geometry, Springer 2003.*

Hatcher, A.: **Algebraic Topology.** *Cambridge University Press 2001.*

Berg de, M., Kreveld van, M., Overmars, M., Schwarzkopf, O.: **Computational Geometry: Algorithms and applications.** *Springer–Verlag, Berlin, 2000.*

Pach, J., Agarwal, P.: **Combinatorial Geometry.** *Cambridge University Press, Cambridge, 1995.*

10. Cryptography

O. Goldreich: **The Foundations of Cryptography - Volume 1, Basic Techniques.** *Cambridge University Press 2001*

O. Goldreich: **The Foundations of Cryptography - Volume 2, Basic Applications.** *Cambridge University Press 2004*

J. Katz, Y. Lindell: **Introduction to Modern Cryptography.** *Second Edition, CRC Press 2014*

11. Data structures

D. P. Mehta, S. Sahni eds.: **Handbook of Data Structures and Applications.** *Chapman Hall/CRC, Computer and Information Series, 2005.*

K. Mehlhorn: **Data Structures and Algorithms I: Sorting and Searching.** *Springer-Verlag, Berlin, 1984.*

12. Algorithmic game theory

Noam Nisan, Tim Roughgarden, Eva Tardos, Vijay V. Vazirani: **Algorithmic Game Theory.** *Cambridge University Press, 2007.*

J. Conway: **On numbers and games.** ¡/I¿AK Peters/CRC Press, 2000.¡/I¿

Study program P4I5A Informatics - visual computing and computer games

Subject Area Board

The current board make up is available at
`http://mff.cuni.cz/phd/or/p4i5` .

Affiliated Institutions

- Institute of Information Theory and Automation of the Czech Academy of Sciences
  Pod vodárenskou věží 4/1143, 182 08 Praha 8
  `http://www.utia.cas.cz/`

Thesis Topic

Thesis topics are listed in SIS at `http://mff.cuni.cz/phd/temata/p4i5` .

Available Courses

Code	Subject	Winter	Summer
NMNM331	**Analysis of Matrix Calculations 1**	2/2 C+Ex	—
NMNM332	**Analysis of Matrix Calculations 2**	—	2/2 C+Ex
NPGR016	**Applied Computational Geometry**	—	2/1 C+Ex
NNUM103	**Fourierova analýza a wavelety**	2/0 Zk	—
NPGR020	**Geometry for Computer Graphics**	—	2/0 Ex
NPGR030	**Optics for computer graphics**	2/0 Ex	—
NPGR010	**Advanced 3D graphics for film and games**	2/2 C+Ex	—
NPGR024	**Seminar on Scientific Soft Skills**	—	0/2 C
NPGR028	**High Performance Ray Tracing**	—	2/0 Zk
NPGR013	**Special Functions and Transformations in Image Processing**	—	2/0 Ex
NPGR005	**Computer graphics and vision seminar**	0/2 C	0/2 C

NPGR022	**Advanced Seminar On Image Processing**	0/2 C	—
NPGR027	**Shading Languages**	—	2/1 C+Ex
NPGR026	**Predictive Image Synthesis Technologies**	—	2/1 C+Ex
NNUM102	**Teorie spline funkcí a waveletů pro doktorandy**	2/0 Zk	—
NPGR025	**Introduction to Colour Science**	2/0 Ex	—
NPGR029	**Variational methods in image processing**	—	2/0 Ex
NPGR023	**Visualization**	2/1 C+Ex	—

State Exam Requirements

Topics 1 - 5 are optionally mandatory in the sense that the student is required to pass an examination of at least one topics 1 and 2, as well as at least one of the topics 3-5. In addition to these, the candidate chooses one topic that was not already picked from topics 1-9, or possibly also others by special agreement with the advisor. The student should pass the state doctoral exam by end of the second year of study.

Optionally mandatory topics (at least one of the topics 1 and 2 as well as at least one of the topics 3-5)

1. Theoretical foundations of computer science

Discrete Mathematics: Graph Theory Fundamentals, Graph Representations in Memory, Graph Algorithms.

Logic, algorithms: Selected algebraic structures. Predicate count. Formal systems, consistency and completeness, Goedel's theorems. Quantifiability theory, Turing machines and equivalent calculation models. Algorithms and their complexity, NP-complete problems. Algorithmically undecidable problems. Theorems about recursion.

2. Mathematical methods for graphics and image processing

Matrix computations: Schur's theorem, meaning of orthogonality and normality, matrix factorisation, methods for solving systems of linear equations, singular decomposition, least squares, partial eigenvalue problem, non-linearity and numerical instability in matrix computing.

Splines: polynomial spline theory, interpolation and smoothing splines, rational splines.

Wavelets: multi-resolution analysis theory, applications, algorithms, biorthogonal wavelets, multidimensional wavelets, wavelet packages, „lifting scheme," continuous wavelet transformation; Mallat's multi-resolution analysis; wavelets with compact support; wavelet examples.

Fourier transformation in L1(R); Wiener's theory of Fourier transformation in L2(R); Paley-Wiener theorem and Heisenberg inequality.

Calculus of Variations Fundamentals (Euler-Lagrange equations, brachistochrone, Lagrange function, function with limited variation)

Fundamentals of numerical methods of problem solving (partial differential equations, finite element method, final differential method, steepest gradient method, conjugated gradients, quadratic programming)

Statistical methods (estimation of probability density function, parametric, non-parametric methods, hypothesis testing)

Geometric transformations, homogeneous coordinates, conversion between coordinate systems in a display pipeline.

3. Fundamentals of computer graphics

Fundamentals of 2D graphics: vision and colours, colorimetry and colour spaces, colour measurements and reproduction, raster graphics, raster image manipulation, raster drawing, anti-aliasing, data structures for 2D search, image and video compression, HDR photography, tone mapping.

Fundamentals of 3D graphics: transformations, representation of 3D scenes, levels of detail, parametric curves and surfaces, visibility, shading, textures, hardware-accelerated graphics, shading programs, CUDA/OpenCL foundation.

Fundamentals of realistic image synthesis: Recursive ray tracing and acceleration methods, data structures, distributed ray tracing, Fundamentals of radiosity, rendering equation and its solution using Monte Carlo methods.

Data visualisation Fundamentals: volumetric data, computer tomography and magnetic resonance, calculation of iso-surfaces, direct volume imaging, volumetric light transport, visualisation of vector fields and tensors of higher order

4. Image analysis fundamentals

Image digitalisation, sampling and quantisation of continuous functions, Shannon's Theorem.

Basic image manipulations, histogram, contrast changes, noise removal, image sharpening.

Linear filtering in spatial and frequency domain, convolution, Fourier transformation.

Edge and corner detection.

Image degradations and their modelling, removal of basic types of degradation (motion blur and defocus), invers and Wiener filter, PSF estimates, blind and multi-channel deconvolution, variational approach.

Image segmentation, classical and variational approaches (thresholding, region growing, Mumford-Shah functional, active contours, level sets).

Registering (matching) images.

Invariants for the description and recognition of 2D objects (general principles, visual features, moments, Fourier descriptors, differential features, moment invariants).

Feature-based recognition theory, supervised and unsupervised classifiers, NN-classifier, linear classifier, SVM classifiers, Bayes classifier. Examples of their use in image analysis.

Cluster analysis in feature space, iterative and hierarchical methods.

Feature space dimensionality reduction, PCA, suboptimal methods for feature selection.

2D wavelet transformation (WT) - mathematical fundamentals.

Using WT to detect edges and features in an image, noise suppression, image registration, and image fusion. Image compression by WT.

5. Fundamentals of 3D vision and robotics

Single-camera computer vision: single perspective camera geometry, projective equations, camera calibration, external and internal parameters, pattern reconstruction from its image.

Stereo-vision: canonical stereo and determination of scene depth, geometry of two cameras, epipolar constraint, fundamental matrix and its determination, solving the problem of stereo correspondence.

Object detection, counting, measurement and tracking: object detection, local features, granulometry, Kalman filter, mean shift.

3D reconstruction of objects: shape from XX (from shading, from multiple light sources, from texture, etc.).

Robot control architecture: motion planning, odometry, SLAM, robot control architecture.

Direct and inverse kinematics: terminology, typical structures, positioning of individual parts of the robot, end-to-end positioning.

Facultative topics

6. Computational geometry

Applied computational geometry: definitions, properties and algorithms for geometric search, convex hull, Voronoi diagram, their applications and generalisations, triangulation in 2D and 3D and their applications, medial axis, surface reconstruction, points of intersection and intersections of geometric objects.

Geometry for computer graphics: Group of projective, affine, and Euclidean transformations. Representation of these groups by matrices. Projective space, homogeneous coordinates. Spherical geometry. Use of quaternions and dual quaternions to describe Euclidean movement.

Curves and surfaces in computer graphics: Spline functions space, Hermit splines, cubic splines, Bézier curves and surfaces, B-spline curves and surfaces, rational curves and surfaces, NURBS, special surfaces, geometric continuity.

7. Realistic image synthesis

Radiometric and photometric quantities, the rendering equation, importance, duality of light transport and importance, operator formulation of light transport and importance. Monte Carlo integration, unbiased Monte Carlo methods for solving the rendering equation (path tracing, light tracing). Combined estimators and applications: direct lighting, bi-directional path tracing. The Metropolis-Hastings method of sampling, Metropolis light transport. Approximate methods for solving the rendering equation: (progressive) photon mapping, (ir)radiance caching, instant radiosity, lightcuts. The Radiance renderer, adaptive refining, hierarchical radiosity, stochastic radiosity. Display of participating media: light transport equations, media display algorithms, special techniques for clouds and atmosphere, translucent materials, BSSRDF. The REYES architecture, RenderMan standard, the principle of shading languages in RenderMan and OpenGL. Predictive image synthesis: error control in rendering pipeline, psycho-physics-faithful tone mapping, simulation of advanced optical phenomena (polarisation, diffraction), fluorescent materials, physical plausibility of shadow language constructs.

8. Invariants for recognition

Geometric moments, definitions and basic characteristics, normalisation. Complex moments. Rotation and image scale moment invariants, completeness, independence, base design. Affine image transformation moment invariants, graph method. Convolution moment invariants, N-fold symmetric kernels, zero space and discrimination. Combined invariants. Moment matching. Orthogonal moments (Legendre moments, Fourier-Mellin moments, Zernike moments). Discrete moments and algorithms to compute them.

9. Computer game development

Game engine architectures: renderer, physics, audio, I/O, network communication, game mechanisms, multi-platform aspects, game content production chain, etc. Examples of existing game engines.

Real-time rendering techniques: calculation of cast shadows, shadow maps, shadow volumes, advanced shadow map techniques (filtering, cascading maps). Deferred shading - principle, advantages, disadvantages. Ambient shading and calculating it in image space.

Advanced real-time shading: BRDF, light reflection equations, function representations, orthogonal and orthonormal bases, spherical harmonics and their use to represent BRDF and lighting, HDR environment map - principle, acquisition, use. Irradiance environment mapping.

Autonomous Agent Architecture. Games as an example of a multi-agent environment.

Representation and game space thinking: environment abstraction (navigation chart, navigation mesh, voxel navigation, visibility representation, environmental propagation), agent navigation in a 3D environment, finding the shortest path (A*, its variants and methods for speeding up calculations), following a path (collision avoidance with static and dynamic objects, reciprocal collision avoidance, steering techniques).

Reactive approaches to managing agents' behaviour: hierarchical final automations, behavioural trees, decision spaces.

Distributing agent behaviour through environment and coordination: smart objects, smart areas, geniuses.

Examples of using scheduling in computer games.

Recommended bibliography

1. Theoretical foundations of computer science

K. Mehlhorn: **Data Structures and Algorithms 2: Graph Algorithms and NP–completeness.** *EATCS – monograph, Springer–Verlag 1984.*

R. E. Tarjan: **Data Structures and Network Algorithms.** *Society for Industrial and Applied Mathematics, Philadelphia 1983.*

J. E. Hopcroft, J. D. Ullman: **Introduction to Automata Theory, Languages, and Computation.** *Addison–Wesley Publ. Company 1979.*

M. R. Garey, D. S. Johnson: **Computers and Intractability: A Guide to the Theory of NP–completeness.** *Freeman, San Francisco 1978.*

O. Demuth, R. Kryl, A. Kučera: **Teorie algoritmů I, II.** *SPN Praha 1989.*

R. I. Soare: **Recursively enumerable sets and degrees.** *Springer–Verlag, Berlin, Heidelberg, New York 1987*

2. Mathematical methods for graphics and image processing
Duintjer Tebbens, J., Hnětynková, I., Plešinger, M., Strakoš, Z., Tichý, P.: **Analýza metod pro maticové výpočty I.** *Skripta MFF UK, 2011.*
Watkins, D.S.: **Fundamentals of Matrix Computations.** *J. Wiley & Sons, New York, Third edition 2010.*
Golub, G.H., Van Loan, C.F.: **Matrix Computations (Third edition).** *J. Hopkins Univ. Press, Baltimore, 1996*
Najzar K.: **Základy teorie waveletů.** *Skripta, Nakl. Karolinum 2004.*
Najzar K.: **Základy teorie splinů.** *Skripta, 2006.*
Micula Ch. and Micula S.: **Handbook of splines.** *1999.*
Resnikoff H. L., Wells R. O., Jr. .: **Wavelets analysis.** *Springer 1998.*
Andreas Antoniou and Wu-Sheng Lu: **Practical Optimization: Algorithms and Engineering Applications.** *Springer, 2007.*
3. Fundamentals of computer graphics
Marschner S., Shirley P.: **Fundamentals of Computer Graphics.** *A K Peters/CRC Press, 4th Revised edition, 2015.*
Shirley P., Morley R. K.: **Realistic Ray Tracing.** *A K Peters, 2nd Revised edition, 2003.*
4. Image analysis fundamentals
Pratt W. K.: **Digital Image Processing (3rd ed.).** *John Wiley, New York, 2001*
Gonzales R. C., Woods R. E.: **Digital Image Processing (2nd ed.).** *Prentice Hall, 2002*
Zitová B., Flusser J.: **Image registration methods: a survey.** *Image and Vision Computing, 21 (2003), 11, pp. 977-1000*
Duda R.O. et al.: **Pattern Classification, (2nd ed.).** *John Wiley, New York, 2001*
Flusser J., Suk T. and Zitová B.: **Moments and Moment Invariants in Pattern Recognition.** *Wiley & Sons Ltd., 2009.*
5. Fundamentals of 3D vision and robotics
Richard Hartley, Andrew Zisserman. **Multiple View Geometry in Computer Vision**, *2nd Edition, Cambridge University Press, 2004.*
Subhash Challa, Mark R. Morelande, Darko Mušicki, Robin J. Evans. **Fundamentals of Object Tracking**, *Cambridge University Press; 1 edition (November 28, 2011).*
Pierre Soille. **Morphological Image Analysis: Principles and Applications**, *Springer (December 7, 2010), ISBN 3-540-65671-5*
6. Computational geometry
O' Rourke, Joseph: **Computational Geometry in C.** *Cambridge University Press, 1.vydání, 1994 nebo 2.vydání, 2000.*
de Berg, Mark, van Kreveld, Marc, Overmars, Mark, Schwarzkopf, Otfried: **Computational Geometry, Algorithms and Applications.** *Springer Verlag, 1.vydání, 1997 nebo 2.vydání, 2001.*
M. Lávička: **KMA/G2 Geometrie 2.** *Pomocný učební text, ZČU Plzeň, 2006*
Jirí Žára a kol: **Moderní počítačová grafika.** *Computer Press, 1998*
František Ježek: **Geometrické a počítačové modelování.** *Plzeň 2009*

7. Realistic image synthesis
Pharr M., Jakob W., Humphreys G.: **Physically Based Rendering: From Theory To Implementation.** *Morgan Kaufmann; 3rd edition, 2016.*
Veach E.: **Robust Monte Carlo Methods for Light Transport Simulation.** *Ph.D. dissertation, Stanford University, 1997.*
Shirley P., Morley R. K.: **Realistic Ray Tracing.** *A K Peters, 2nd Revised edition, 2003.*
Dutre P., Bala K., Bekaert P.: **Advanced Global Illumination.** *A k Peters, 2nd edition, 2006.*
Glassner A.: **Principles of Digital Image Synthesis.** *Addison- Wesley, 1995.*
Jensen H.W.: **Realistic Image Synthesis Using Photon Mapping.** *A K Peters, 2001.*
8. Invariants for recognition
J. Flusser, T. Suk and B. Zitová: **Moments and Moment Invariants in Pattern Recognition.** *Wiley & Sons Ltd., 2009.*
J. Flusser, T. Suk and B. Zitová, **2D and 3D Image Analysis by Moments**, *Wiley Sons Ltd., 2016.*
9. Computer game development
Gregory, Jason. **Game engine architecture**. *AK Peters/CRC Press, 2014.*
Nystrom, Robert. **Game programming patterns**. *Genever Benning, 2014.*
Millington, Ian, and John Funge. **Artificial intelligence for games**. *CRC Press, 2009.*
Rabin, Steve (ed.): **AI Game Programming Wisdom series, Charles River Media**, *2002-2008.*
Rabin, Steve (ed.). **Game AI Pro: Collected Wisdom of Game AI professionals series**, *AK Peters/CRC Press, 2013-2017*
Tomas Akenine-Moller, Eric Haines, Naty Hoffman. **Real-Time Rendering**, *A K Peters/CRC Press; 4th edition 2018.*