**EE 4328-006**

**Op-Amps in Analog**

**Signal Paths**

Spring 2015

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**Topics:**

This senior-level course covers the fundamental concepts involved in the analysis and design of a wide variety of linear and non-linear circuits that use bipolar and CMOS integrated circuit operational amplifiers (op-amps). Applications of these components in practical circuit designs are emphasized. Presented in the first part of this course are op-amp fundamentals consisting of definitions, op-amp types (VFOA, CFOA), fabrication processes, building blocks, data sheet parameters, models, and dc biasing methods. Methods and circuits for op-amp testing and parameter measurement are also included. More complex circuits such as difference amplifiers, precision instrumentation amplifiers, transimpedance and transadmittance amplifiers, summers, and integrators are included. This part of the course concludes with applications of the op-amp in non-linear circuits such as comparators, Schmitt triggers and rectifiers, and signal generators such as sine-wave, square-wave, and triangle-wave generators.

The second part of this course covers specific applications of op-amps in the design of continuous-time analog active RC filters. Topics to be covered include approximation functions, prototype circuits, frequency transformations, active devices and models, and sensitivity functions and their applications to filter designs. Design methodologies of high-order active filters are included with the analysis and design of single and multiple-amplifier biquads (SABs and MABs), and the implementation of FDNR circuits for ladder simulation.

Students successfully completing this course will be professionally prepared in the analysis and design of a variety of op-amp circuits. This includes how to read, interpret, and understand parameters listed on op-amp data sheets. Students will also be able to analyze and design op-amp models, biasing circuits, test and measurement circuits, linear and non-linear circuits using op-amps, and advanced op-amp topologies.

**Prerequisites:**

EE 3446.

**Textbooks:**

1. H.T. Russell, Jr., *Operational Amplifiers: Designs and Applications*, OPALtx, 2008.

2. S. Franco, *Design with Operational Amplifiers and Analog Integrated Circuits, 3nd Edition*, The McGraw-Hill Companies, Inc., New York, NY, 2001.

3. H.T. Russell, Jr., *Analysis and Design of Continuous-Time Active RC Filters*, OPAL Engineering, Inc., 1995.

**Tools:**

1. Scientific calculator. Calculators as components in communication devices are not suggested nor allowed on exams.

2. Breadboard (mandatory).

3. Toolbox (mandatory) – containing an assortment of electronics tools consisting of needle nose pliers, diagonal cutters, tweezers, precision knife set, pocket screwdrivers.

4. MATLAB and Simulink Student Version (optional).

5. A good web browser.

**Times and Locations:**

*Section 006 Lecture* – Monday, Wednesday, and Friday, 8:00 am to 8:50 am, NH110.

**GTAs:**

*Lecture and lab*: TBD.

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| **EE 4328-006****Lecture Schedule** |
| **Week/Date** | **Topics** | **Reading Assignment** |
| 1 | 1-19 | *Op-amp fundamentals* – Op-amp definitions, types; process technologies; VFOA building blocks and circuits; large-signal dc and small-signal ac parameters. | 1. Ch. 1 – 1.1.1; A.1 to A.22. Ch. 1 – 1.1 to 1.22. Ch. 5 |
| 2 | 1-26 | CMRR and PSRR; transient parameters; slew-rate; VFOA vs CFOA; CFOA topologies; CMOS topology. | 1. Ch. 1 – 1.1.2 to 1.2.1;A.3 to A.42. Ch. 6 |
| 3 | 2-2 | Low-level models for pencil and paper applications; high-level models for CAD; dc biasing methods and circuits; Op-amp test circuits; parameter measurements. | 1. Ch. 2 and 3; Ch. 42. Ch. 1 – 1.8 |
| 4 | 2-9 | *Linear circuit applications* – low-frequency inverting and non-inverting gain configurations; voltage gains, input and output impedances. | 1. Ch. 5 – 5.1 to 5.22. Ch. 1 – 1.3 to 1.7 |
| 5 | 2-16 | High-frequency inverting gain and non-inverting gain configurations; Bode plots; CFOA small-signal open-loop frequency response characteristics; models and data sheet parameters. | 1. Ch. 5 – 5.3 to 5.5 |
| 6 | 2-23 | Difference and differential amplifiers, instrumentation amplifiers, transimpedance amplifiers, summers and integrators.**Mid-Term Exam 1** | 1. Ch. 5 – 5.52. Ch. 2 – 2.1 to 2.42. Ch. 6 – 6.7 |
| 7 | 3-2 | *Non-linear circuit applications* – voltage comparators; positive feedback; Schmitt triggers; half-wave and full-wave rectifiers; signal generators; sine-wave, square-wave and triangle-wave oscillators. | 2. Ch. 9 – 9.1 to 9.42. Ch. 10 – 10.1 to 10.2 |
| 8 | 3-9 | **Spring Break** |  |
| 9 | 3-16 | *Filter basics* – definitions, specifications, the low-pass prototype; passive low-pass ladder filters; impedance and frequency scaling; network response functions; pole and zero locations. | 3. Ch. 1 – 1.1 |
| 10 | 3-23 | Frequency domain approximations in the pass band (Butterworth, Chebyshev, Bessel); algorithms for frequency transformation (LP to LP and LP to HP). | 3. Ch. 1 – 1.2 to 1.3 |
| 11 | 3-30 | Algorithms for frequency transformation (LP to BP and LP to BR); active devices for filter designs – operational am­plifiers, gyrators, inductor simulators, and FDNR's.**Mid-Term Exam 2** | 3. Ch. 1 – 1.2 to 1.3 |
| 12 | 4-6 | Sensitivity concepts; derivation of single parameter sensitivi­ty functions; application of sensitivity functions to worse-case design. | 3. Ch. 2 – 2.2 |
| 13 | 4-13 | The biquadratic (biquad) filter response functions; single amplifier biquadratic (SAB) realizations; dual and multiple amplifier biquad (MAB) realizations. | 3. Ch. 2 – 3.1 to 3.3 |
| 14 | 4-20 | State-variable biquad realizations; group delay equalizers; review of passive terminated LC ladder filters; inductance simulations. | 3. Ch. 4 – 4.1 |
| 15 | 4-27 | GIC and FDNR implementations; a design example – the ladder realization of a 5-th order Cauer-Chebyshev response function. | 3. Ch. 4 – 4.2 to 4.33. Ch. 5 – 5.1 |
| 16 | 5-4 | A design example – the cascade realization of a 5-th order Cauer-Chebyshev response function. | 3. Ch. 5 – 5.1 |
| 17 | 5-11 | **Final Exam****Friday May 15, 2015****8:00 am to10:30 am** |  |

**References:**

*Op-amps*:

1. P.R. Gray, P.J. Hurst, S.H. Lewis, and R.G. Meyer, *Analysis and Design of Analog Integrated Circuits, Fourth Edition*, John Wiley & Sons, Inc., New York, NY, 2001.

2. A.B. Grebene, *Bipolar and MOS Analog Integrated Circuit Design*, John Wiley and Sons, Inc., New York, NY, 1984.

3. J.K. Roberge, *Operational Amplifiers: Theory and Practice*, John Wiley and Sons, Inc., New York, NY, 1975.

4. J.R. Hufault, *Op-Amp Network Design*, John Wiley and Sons, Inc., New York, NY, 1986.

5. R.G. Irvine, *Operational Amplifier Characteristics and Applications*, Prentice-Hall, Inc., New York, NY, 1987.

6. R.A. Gayakwad, *Op-Amps and Linear Integrated Circuits, Second Edition*, Prentice-Hall, Inc., New York, NY, 1988.

7. W.G. Jung, *IC Op-Amp Cook Book, Third Edition*, Howard W. Sams and Co., New York, NY, 1986.

*Active RC filters*:

1. W.K. Chen, *Passive and Active Filters: Theory and Implementation*, John Wiley and Sons, Inc., New York, NY, 1986.

2. G.C. Temes and J.W. LaPatra, *Introduction to Circuit Synthesis and Design*, McGraw-Hill Book Co., Inc., New York, NY, 1977.

3. G.C. Temes and S.K. Mitra, *Modern Filter Theory and Design*, John Wiley and Sons, Inc., New York, NY, 1973.

4. R.W. Daniels, *Approximation Methods for Electronic Filter Design*, McGraw-Hill Book Co., Inc., New York, NY, 1974.

5. S.K. Mitra, *Analysis and Design of Linear Active Networks*, John Wiley and Sons, Inc., New York, NY, 1969.

6. L.P. Huelsman, *Theory and Design of Active RC Circuits*, McGraw-Hill Book Co., Inc., New York, NY, 1968.

7. G. Daryanani, *Principles of Active Network Synthesis and Design*, John Wiley and Sons, Inc., New York, NY, 1976.

8. M.S. Ghausi and K.R. Laker, *Modern Filter Design: Active RC and Switched Capacitor*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1981.

9. R.C. Dorf and J.A. Svoboda, Introduction to Electric Circuits, *7th Edition*, John Wiley & Sons, Inc., 2006, ISBN-10 0-471-73042-2.

**Student Learning Outcomes:**

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| **EE 4328-006**Course Learning Objectivesand Assessment Approach |
| Number | Course Learning Objective (CLO) | ABETOutcome | AssessmentApproach |
| 1 | An understanding of op-amp fundamentals. | a, e | exam problems |
| 2 | An understanding of the op-amp theory of operation. | a, e | exam problems |
| 3 | An understanding of op-amp data sheet parameters. | a, e | exam problems |
| 4 | An understanding of op-amp test circuits. | a, e | exam problems |
| 5 | An understanding of inverting and non-inverting gain configurations. | a, e | exam problems |
| 6 | An understanding of op-amp linear circuit applications. | a, e | exam problems |
| 7 | An understanding of op-amp non-linear circuit applications. | a, e | exam problems |
| 8 | An understanding of filter fundamentals. | a, e | exam problems |
| 9 | An understanding of filter specifications. | a, e | exam problems |
| 10 | An understanding of op-amp applications in active RC filters designs. | a, e | exam problems |
| 11 | The application of computer tools and software in the solution of op-amp design problems. | a, k | labs |
| 12 | A working understanding of important analytical principles. | a, b, c | labs |

Outcomes a-k

(a-k as listed by ABET)

a. an ability to apply knowledge of mathematics, science, and engineering;

b. an ability to design and construct experiments, as well as to analyze and interpret data;

c. an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability;

d. an ability to function on multidisciplinary teams;

e. an ability to identify, formulate, and solve engineering problems;

f. an understanding of professional and ethical responsibility;

g. an ability to communicate effectively;

h. the broad education necessary to understand the impact of engineering solutions in a global and societal context;

i. a recognition of the need for, and an ability to engage in lifelong learning;

j. a knowledge of contemporary issues;

k. an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

**General Lecture Section Information:**

1. There are 31 class meetings scheduled for the 17 weeks of the 2015 Spring Semester. Twenty eight of these meetings are devoted to in-class lectures, three devoted to examinations – two mid-terms and one final. The ninth week is reserved for Spring Break. There will be no class meetings that week.

2. Your 100% attendance in lectures is mandatory and required. This requirement will not be waived for any reason.

3. There will be five to six homework assignments, usually given on two-week intervals. Each assignment requires about five to ten hours for completion. These assignments will be graded and will be included as part of your total course grade. Past experience has shown that students who spend the necessary time to work these assignments usually do quite well on the examinations. Solutions to homework problems will be e-mailed to all students by the end of the day the assignment is due. Homework turned in after the solutions have been sent out will not be counted and will receive a grade of zero.

4. Mid-term examinations will be given on the 6th and 11th weeks, and will be one hour written exercises.

5. The final examination will be given on **Friday May 15 2015** and will be a comprehensive written examination. **NOTICE**: The UTA registrar has demanded a firm, unforgivable final date (four calendar days after the last final examination date) for the submission of course grades from all instructors. Because of this rigid schedule, the date planned for the final examination (**Friday May 13, 2015 8:00 am to 10:30 am**) is fixed and will not be changed for any reason. Therefore, all students, without exception, **must** take the final examination at this time.

6. You are respectively requested to turn off any and all communication devices while in the Lecture Sections. Communication devices of any type are not allowed to be used on any and all exams. No exceptions. Calculators without communication capability are permitted.

7. All examinations will be pencil, paper, and calculator exercises. All students will take these exams at the scheduled times in the classroom.

8. There will be absolutely no late or make-up mid-term examinations given unless a written request has been submitted to and approved by the instructor at least two weeks prior to the examination date. As a rule, make-up examinations are several orders of magnitude more difficult than examinations given on the scheduled dates. Please be advised that illness or any other absence on the examination date does not constitute a valid reason for a make-up examination.

9. The *total grade* (T) for this course is based upon the grades for homework, two mid-term exams, and the final exam. The total T is computed from

  (1)

10. Failure to take (either scheduled or approved make-up) any or all exams (mid-terms and final) will automatically result in a letter grade of ‘F’ for the course. You are required to take all exams.

11. Office hours are posted outside my office (NH526). If you have any questions and/or adverse difficulty with the lectures or class material, I strongly suggest that you call or e-mail me (during regular working hours, of course). If necessary, a scheduled office visit can be arranged.

12. Additional important dates:

 Census date – **Wednesday, February 4, 2015**.

 Last day to drop classes – **Friday, April 3, 2015**.

 Registration begins for Summer and Fall 2015 Terms – **Wednesday April 6, 2015**.

 Last day of classes – **Friday, May 8, 2015**.

**Drop Policy:**

Please refer to the University policy for dropping courses.

**Americans With Disabilities Act:**

The University of Texas at Arlington is on record as being committed to both the spirit and letter of federal equal opportunity legislation; reference Public Law 92-112 - The Rehabilitation Act of 1973 as amended. With the passage of federal legislation entitled *Americans with Disabilities Act (ADA)*, pursuant to section 504 of the Rehabilitation Act, there is renewed focus on providing this population with the same opportunities enjoyed by all citizens. As a faculty member, I am required by law to provide "reasonable accommodations" to students with disabilities, so as not to discriminate on the basis of that disability. Student responsibility primarily rests with informing faculty of their need for accommodation and in providing authorized documentation through designated administrative channels.  Information regarding specific diagnostic criteria and policies for obtaining academic accommodations can be found at [www.uta.edu/disability](http://www.uta.edu/disability). Also, you may visit the Office for Students with Disabilities in room 102 of University Hall or call them at (817) 272-3364.

**Student Support Services Available:**

The University of Texas at Arlington supports a variety of student success programs to help you connect with the University and achieve academic success. These programs include learning assistance, developmental education, advising and mentoring, admission and transition, and federally funded programs. Students requiring assistance academically, personally, or socially should contact the Office of Student Success Programs at 817-272-6107 for more information and appropriate referrals.

**Final Review Week:**

A period of five class days prior to the first day of final examinations in the long sessions shall be designated as Final Review Week. The purpose of this week is to allow students sufficient time to prepare for final examinations. During this week, there shall be no scheduled activities such as required field trips or performances; and no instructor shall assign any themes, research problems or exercises of similar scope that have a completion date during or following this week unless specified in the class syllabi. During Final Review Week, an instructor shall not give any examinations constituting 10% or more of the final grade, except makeup tests and laboratory examinations. In addition, no instructor shall give any portion of the final examination during Final Review Week. Classes are held as scheduled during this week and lectures and presentations may be given.

**E-Culture Policy:**

The University of Texas at Arlington has adopted the University email address as an official means of communication with students. Through the use of email, UT-Arlington is able to provide students with relevant and timely information, designed to facilitate student success. In particular, important information concerning registration, financial aid, payment of bills, and graduation may be sent to students through email. All students are assigned an email account and information about activating and using it is available at [www.uta.edu/email](http://www.uta.edu/email). New students (first semester at UTA) are able to activate their email account 24 hours after registering for courses. There is no additional charge to students for using this account, and it remains active as long as a student is enrolled at UT-Arlington. Students are responsible for checking their email regularly.

**Ethics:**

### Student Responsibility

Undergraduate and graduate students assume full responsibility for knowledge of all University rules, regulations and deadlines published in the Undergraduate and Graduate Catalogs and of all departmental and program requirements concerning their degree programs.

### Academic Dishonesty

All students are expected to pursue their academic careers with honesty and integrity. Academic dishonesty includes, but is not limited to, cheating on a test or other coursework, plagiarism (offering the work of another as one's own) and unauthorized collaboration with another person. Students found responsible for dishonesty in their academic pursuits are subject to penalties that may range from disciplinary probation, suspension or expulsion from the University. In accordance with the Rules and Regulations of the Board of Regents of The University of Texas System (Part One, Chapter VI), institutional procedures regarding allegations of academic dishonesty are outlined in Part Two, Chapter 2, of the U.T. Arlington Handbook of Operating Procedures. This information may be obtained by accessing the Dean of Students' Web site at www.uta.edu/studentaffairs/dos or the Student Judicial Affairs' Web site at www.uta.edu/studentaffairs/judicial affairs. Copies of each regulation can be obtained in the Dean of Students' Office on the lower level of the University Center.

**Definitions (UTA Handbook of Operating Procedures)**

F. scholastic dishonesty, including, but not limited to, cheating on an examination or an assignment, plagiarism, and collusion;

1. *cheating on an examination or an assignment* includes:

 a. copying the work of another, engaging in written, oral or any other means of communication with another, or giving aid to or seeking aid from another when not permitted by the instructor;

 b. using material during an examination or when completing an assignment that is not authorized by the person giving the examination or making the work assignment;

 c. taking or attempting to take an examination for another, or allowing another to take or attempt to take an examination for a student;

 d. using, obtaining, or attempting to obtain by any means, the whole or any part of an un-administered examination or work assignment;

 e. any act designed to give unfair advantage to a student or the attempt to commit such an act;

2. *plagiarism* means the unacknowledged incorporation of the work of another in work that is offered for credit;

3. *collusion* means the unauthorized collaboration with another in preparing work that is offered for credit.

The following is an excerpt from the College of Engineering's statement on Ethics, Professionalism, and Conduct of Engineering Students. Read the statement carefully, sign it, and return it to your instructor. You may make a copy for your records. Additional copies of this statement can be obtained from your instructor or the Office of the Dean of Engineering.

**STATEMENT ON ETHICS, PROFESSIONALISM, AND CONDUCT**

**FOR ENGINEERING STUDENTS**

COLLEGE OF ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

The College cannot and will not tolerate any form of academic dishonesty by its students. This includes, but is not limited to cheating on examination, plagiarism, or collusion.

**Cheating** on an examination includes:

1. Copying from another's paper, any means of communication with another during examination, giving aid to or receiving aid from another during examination;

2. Using any material during examination that is unauthorized by the proctor;

3. Taking or attempting to take an examination for another student or allowing another student to take or attempt to take an examination for oneself.

4. Using, obtaining, or attempting to obtain by any means the whole or any part of an un-administered examination.

**Plagiarism** is the unacknowledged incorporation of another's work into work which the student offers for credit.

**Collusion** is the unauthorized collaboration of another in preparing work that a student offers for credit.

I have read and I understand the above statement.

In addition, I understand that, in order to ensure fairness to all students, exams will be proctored and possibly videotaped.

Course and section number: \_\_\_\_EE 4328-006\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

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Student's signature: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Student's name, printed: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Student’s ID number: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Student’s e-mail address: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

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