

Contents

		page
11	4N.4 Add quantitative detail: use beta explicitly	155
18	4N.5 A strikingly different transistor circuit: the switch	158
18	4N.6 Recapitulation: the important transistor circuits at a glance	166
18	4N.7 AoE Reading	167
24	Lab: Transistors I	168
28	4L.1 Transistor preliminaries: look at devices	169
30	4L.2 Emitter follower	170
Preface	4L.3 Current source	xx
Overview, as the Course begins		xxx
100		1
102	Part I Analog: Passive Devices	1
1N	DC Circuits	3
108	1N.1 Overview	3
108	1N.2 Three laws	5
109	1N.3 First application: voltage divider	11
112	1N.4 Loading, and “output impedance”	14
113	1N.5 Readings in AoE	24
118		188
1L	Lab: DC Circuits	25
123	1L.1 Ohm’s law	25
126	1L.2 Voltage divider	26
130	1L.3 Converting a meter movement into a voltmeter and ammeter	27
131	1L.4 The diode	29
131	1L.5 I versus V for some mystery boxes	30
133	1L.6 Oscilloscope and function generator	32
1S	Supplementary Notes: Resistors, Voltage, Current	35
132	1S.1 Reading resistors	35
136	1S.2 Voltage versus current	38
1W	Worked Examples: DC circuits	42
138	1W.1 Design a voltmeter, current meter	42
139	1W.2 Resistor power dissipation	44
141	1W.3 Working around imperfections of instruments	45
141	1W.4 Thevenin models	47
141	1W.5 “Looking through” a circuit fragment, and R_{in} , R_{out}	48
144	1W.6 Effects of loading	49
145		235
2N	RC Circuits	51
146	2N.1 Capacitors	51
147	2N.2 Time-domain view of RCs	53
147	2N.3 Frequency domain view of RCs	58
147	2N.4 Blocking and decoupling	74

2N.5	A somewhat mathy view of RC filters	76
2N.6	Readings in AoE	77
2L	Labs: Capacitors	78
2L.1	Time-domain view	78
2L.2	Frequency domain view	81
2S	Supplementary Notes: RC Circuits	85
2S.1	Reading capacitors	85
2S.2	C notes: trying for an intuitive grip on capacitors' behavior	90
2S.3	Sweeping frequencies	93
2W	Worked Examples: RC Circuits	100
2W.1	RC filters	100
2W.2	RC step response	105
3N	Diode Circuits	108
3N.1	Overloaded filter: another reason to follow our $10\times$ loading rule	108
3N.2	Scope probe	109
3N.3	Inductors	112
3N.4	LC resonant circuit	113
3N.5	Diode Circuits	118
3N.6	The most important diode application: DC from AC	119
3N.7	The most important diode application: (unregulated-) power supply	123
3N.8	Radio!	126
3N.9	Readings in AoE	130
3L	Lab: Diode Circuits	131
3L.1	LC resonant circuit	131
3L.2	Half-wave rectifier	133
3L.3	Full-wave bridge rectifier	134
3L.4	Design exercise: AM radio receiver (fun!)	135
3L.5	Signal diodes	136
3S	Supplementary Notes and Jargon: Diode Circuits	138
3S.1	A puzzle: why LC 's ringing dies away despite Fourier	138
3S.2	Jargon: passive devices	139
3W	Worked Examples: Diode Circuits	141
3W.1	Power supply design	141
3W.2	Z_{IN}	144
Part II	Analog: Discrete Transistors	149
4N	Transistors I	151
4N.1	Overview of Days 4 and 5	151
4N.2	Preliminary: introductory sketch	154

4N	4N.3 The simplest view: forgetting beta 4N.4 Add quantitative detail: use beta explicitly 4N.5 A strikingly different transistor circuit: the switch 4N.6 Recapitulation: the important transistor circuits at a glance 4N.7 AoE Reading	155 158 166 167 168
4L	Lab: Transistors I 4L.1 Transistor preliminaries: look at devices out of circuit 4L.2 Emitter follower 4L.3 Current source 4L.4 Common-emitter amplifier 4L.5 Transistor switch 4L.6 A note on power supply noise	169 169 170 172 172 174 176
4W	Worked Examples: Transistors I 4W.1 Emitter follower 4W.2 Phase splitter: input and output impedances of a transistor circuit 4W.3 Transistor switch	178 178 181 185
5N	Transistors II 5N.1 Some novelty, but the earlier view of transistors still holds 5N.2 Reviewish: phase splitter 5N.3 Another view of transistor behavior: Ebers–Moll 5N.4 Complication: distortion in a high-gain amplifier 5N.5 Complications: temperature instability 5N.6 Reconciling the two views: Ebers–Moll meets $I_C = \beta \times I_B$ 5N.7 “Difference” or “differential” amplifier 5N.8 Postscript: deriving r_e 5N.9 AoE Reading	188 188 189 190 194 196 201 201 207 208
5L	Lab: Transistors II 5L.1 Difference or differential amplifier	209 209
5S	Supplementary Notes and Jargon: Transistors II 5S.1 Two surprises, perhaps, in behavior of differential amp 5S.2 Current mirrors; Early effect 5S.3 Transistor summary 5S.4 Important circuits 5S.5 Jargon: bipolar transistors	220 220 222 230 232 235
5W	Worked Examples: Transistors II 5W.1 High-gain amplifiers 5W.2 Differential amplifier 5W.3 Op-amp innards: diff-amp within an IC operational amplifier 5W.5 Quantitative effects of feedback	237 237 238 239 396

Part III	Analog: Operational Amplifiers and their Applications	243
6N	Op-amps I	245
6N.1	Overview of feedback	245
6N.2	Preliminary: negative feedback as a general notion	248
6N.3	Feedback in electronics	249
6N.4	The op-amp golden rules	251
6N.5	Applications	252
6N.6	Two amplifiers	252
6N.7	Inverting amplifier	254
6N.8	When do the Golden Rules apply?	256
6N.9	Strange things can be put into feedback loop	259
6N.10	AoE Reading	261
6L	Lab: Op-Amps I	262
6L.1	A few preliminaries	262
6L.2	Open-loop test circuit	263
6L.3	Close the loop: follower	263
6L.4	Non-inverting amplifier	265
6L.5	Inverting amplifier	265
6L.6	Summing amplifier	266
6L.7	Design exercise: unity-gain phase shifter	266
6L.8	Push-pull buffer	268
6L.9	Current to voltage converter	269
6L.10	Current source	271
6W	Worked Examples: Op-Amps I	273
6W.1	Basic difference amp made with an op-amp	273
6W.2	A more exotic difference amp	276
6W.3	Problem: odd summing circuit	277
7N	Op-amps II: Departures from Ideal	280
7N.1	Old: subtler cases, for analysis	281
7N.2	Op-amp departures from ideal	284
7N.3	Four more applications	294
7N.4	Differentiator	300
7N.5	Op-amp Difference Amplifier	301
7N.6	AC amplifier: an elegant way to minimize effects of op-amp DC errors	301
7N.7	AoE Reading	302
7L	Labs: Op-Amps II	303
7L.1	Integrator	303
7L.2	Differentiator	306
7L.3	Slew rate	308
7L.4	AC amplifier: microphone amplifier	308
7S	Supplementary Notes: Op-Amp Jargon	310

7W	Worked Examples: Op-Amps II	311
104	7W.1 The problem	311
204	7W.2 Op-amp millivoltmeter	314
128	12L.3 Switching audio amplifier	495
8N	Op-Amps III: Nice Positive Feedback	319
125	8N.1 Useful positive feedback	319
804	8N.2 Comparators	320
804	8N.3 RC relaxation oscillator	327
410	8N.4 Sine oscillator: Wien bridge	331
135	8N.5 AoE Reading	335
125	13N.2 One concern for everyone: stability	506
8L	Lab. Op-Amps III	336
125	8L.1 Two comparators	336
125	8L.2 Op-amp RC relaxation oscillator	338
425	8L.3 Easiest RC oscillator, using IC Schmitt trigger	339
828	8L.4 Apply the sawtooth: PWM motor drive	340
425	8L.5 IC RC relaxation oscillator: '555	341
904	8L.6 '555 for low-frequency frequency modulation ("FM")	342
435	8L.7 Sinewave oscillator: Wien bridge	343
14N	Logic Gates	513
8W	Worked Examples: Op-Amp III	345
434	8W.1 Schmitt trigger design tips	345
984	8W.2 Problem: heater controller	348
144	14N.4 The usual way to do digital logic: programming logic	526
9N	Op-Amps IV: Parasitic Oscillations; Active Filter	353
444	9N.1 Introduction	353
442	9N.2 Active filters	354
420	9N.3 Nasty "parasitic" oscillations: the problem, generally	356
141	9N.4 Parasitic oscillations in op-amp circuits	356
121	9N.5 Op-amp remedies for keeping loops stable	361
121	9N.6 A general criterion for stability	365
121	9N.7 Parasitic oscillation without op-amps	367
121	9N.8 Remedies for parasitic oscillation	370
121	9N.9 Recapitulation: to keep circuits quiet...	372
121	9N.10 AoE Reading	372
9L	Labs. Op-Amps IV	373
121	9L.1 VCVS active filter	373
121	9L.2 Discrete transistor follower	374
121	9L.3 Op-amp instability: phase shift can make an op-amp oscillate	376
121	9L.4 Op-amp with buffer in feedback loop	378
9S	Supplementary Notes. Op-Amps IV	380
124	9S.1 Op-amp frequency compensation function	380
122	9S.2 Active filters: how to improve a simple RC filter	384
128	9S.3 Noise: diagnosing fuzz	389
128	9S.4 Annotated LF411 op-amp schematic	395
128	9S.5 Quantitative effects of feedback	396

9W	Worked Examples: Op-Amps IV	401
9W.1	What all that op-amp gain does for us	401
9W.2	Stability questions	402
	245	
10N	Op-Amps V: PID Motor Control Loop	407
10N.1	Examples of real problems that call for this remedy	408
10N.2	The PID motor control loop	408
10N.3	Designing the controller (custom op-amp)	410
10N.4	Proportional-only circuit: predicting how much gain the loop can tolerate	412
10N.5	Derivative, D	415
10N.6	AoE Reading	420
	238	
10L	Lab. Op-Amps V	421
10L.1	Introduction: why bother with the PID loop?	421
10L.2	PID motor control	422
10L.3	Add derivative of the error	428
10L.4	Add integral	430
10L.5	Scope images: effect of increasing gain, in P-only loop	432
	238	
11N	Voltage Regulators	433
11N.1	Evolving a regulated power supply	434
11N.2	Easier: 3-terminal IC regulators	439
11N.3	Thermal design	441
11N.4	Current sources	443
11N.5	Crowbar overvoltage protection	444
11N.6	A different scheme: switching regulators	445
11N.7	AoE Readings	450
	276	
11L	Lab: Voltage Regulators	451
11L.1	Linear voltage regulators	451
11L.2	A switching voltage regulator	457
	281	
11W	Worked Examples: Voltage Regulators	462
11W.1	Choosing a heat sink	462
11W.2	Applying a current-source IC	463
	309	
12N	MOSFET Switches	465
12N.1	Why we treat FETs as we do	465
12N.2	Power switching: turning something ON or OFF	469
12N.3	A power switch application: audio amplifier	471
12N.4	Logic gates	473
12N.5	Analog switches	474
12N.6	Applications	475
12N.7	Testing a sample-and-hold circuit	480
12N.8	AoE Reading	485
	302	

12L	Lab: MOSFET Switches	486
232	12L.1 Power MOSFET	486
282	12L.2 Analog switches	489
283	12L.3 Switching audio amplifier	495
284	Worked Examples: Memory	
12S	Supplementary Notes: MOSFET Switches	497
285	12S.1 A physical picture	497
13N	Group Audio Project	503
286	13N.1 Overview: a day of group effort	503
288	13N.2 One concern for everyone: stability	506
289	13N.3 Sketchy datasheets for LED and phototransistor	507
290	18N.2 Digital \leftrightarrow analog converters	693
13L	Lab: Group Audio Project	508
291	13L.1 Typical waveforms	508
292	13L.2 Debugging strategies	509
293	18N.6 Dither	714
Part IV	Digital: Gates, Flip-Flops, Counters, PLD, Memory	511
294	18N.8 AoE Reading	723
14N	Logic Gates	513
295	14N.1 Analog versus digital	513
296	14N.2 Number codes: Two's-complement	518
297	14N.3 Combinational logic	520
298	14N.4 The usual way to do digital logic: programmable arrays	526
299	14N.5 Gate types: TTL and CMOS	528
300	14N.6 Noise immunity	530
301	14N.7 More on gate types	533
302	14N.8 AoE Reading	535
303	18S.4 Explanations	739
14L	Lab: Logic Gates	537
304	14L.1 Preliminary	537
305	14L.2 Input and output characteristics of integrated gates: TTL and CMOS	540
306	14L.3 Pathologies	541
307	14L.4 Applying IC gates to generate particular logic functions	543
308	14L.5 Gate innards; looking within the black box of CMOS logic	544
309	19L.1 A digital world	749
14S	Supplementary Notes: Digital Jargon	548
Part VI	Microcontrollers	
14W	Worked Examples: Logic Gates	550
310	14W.1 Multiplexing: generic	550
311	14W.2 Binary arithmetic	554
312	20N.2 Elements of a minimal machine	760
15N	Flip-Flops	567
313	15N.1 Implementing a combinational function	568
314	15N.2 Active-low, again	569
315	15N.3 Considering gates as “Do this/do that” functions	573
316	15N.4 XOR as Invert/Pass* function	574
317	20N.8 AoE Reading	778

15N.5	OR as Set/Pass* function	575
15N.6	Sequential circuits generally, and flip-flops	575
15N.7	Applications: more debouncers	582
15N.8	Counters	583
15N.9	Synchronous counters	584
15N.10	Another flop application: shift-register	586
15N.11	AoE Reading	587
15L	Lab: Flip-Flops	588
15L.1	A primitive flip-flop: SR latch	588
15L.2	D type	588
15L.3	Counters: ripple and synchronous	591
15L.4	Switch bounce, and three debouncers	592
15L.5	Shift register	594
15S	Supplementary Note: Flip-Flops	597
15S.1	Programmable logic devices	597
15S.2	Flip-flop tricks	599
16N	Counters	603
16N.1	Old topics	603
16N.2	Circuit dangers and anomalies	607
16N.3	Designing a larger, more versatile counter	610
16N.4	A recapitulation of useful counter functions	614
16N.5	Lab 16L's divide-by-N counter	615
16N.6	Counting as a digital design strategy	616
16L	Lab: Counters	617
16L.1	A fork in the road: two paths into microcontrollers	617
16L.2	Counter lab	619
16L.3	16-bit counter	621
16L.4	Make horrible music	629
16L.5	Counter applications: stopwatch	631
16W	Worked Examples: Applications of Counters	634
16W.1	Modifying count length: strange-modulus counters	634
16W.2	Using a counter to measure period, thus many possible input quantities	636
16W.3	Bullet timer	642
17N	Memory	648
17N.1	Buses	648
17N.2	Memory switch application: audio amplifier	651
17N.3	State machine: new name for old notion	655
17L	Lab: Memory	661
17L.1	RAM	661
17L.2	State machines	663
17L.3	State machine using a PAL programmed in Verilog	669

17S	Supplementary Notes: Digital Debugging and Address Decoding	671
17S.1	Digital debugging tips	671
17S.2	Address decoding	675
17S.3	Lab Micro 4. Interrupts; ADC and DAC	920
17W	Worked Examples: Memory	678
17W.1	A sequential digital lock	678
17W.2	Solutions	681
17W.3	Supplementary Notes: Micro 4	946
Part V	Digital: Analog-Digital, PLL, Digital Project Lab	687
18N.1	Interfacing among logic families	689
18N.2	Digital \leftrightarrow analog conversion, generally	693
18N.3	Digital to analog (DAC) methods	697
18N.4	Analog-to-digital conversion	701
18N.5	Sampling artifacts	712
18N.6	Dither	714
18N.7	Phase-locked loop	716
18N.8	AoE Reading	723
18N.9	Lab Micro 5. Moving Pointers, Serial Buses	975
18L	Lab: Analog \leftrightarrow Digital; PLL	724
18L.1	Analog-to-digital converter	724
18L.2	Phase-locked loop: frequency multiplier	729
18L.3	Supplementary Note: Dallas Program Counter	975
18S	Supplementary Notes: Sampling Rules; Sampling Artifacts	734
18S.1	What's in this chapter?	734
18S.2	General notion: sampling produces predictable artifacts in the sampled data	734
18S.3	Examples: sampling artifacts in time- and frequency-domains	735
18S.4	Explanation? The images, intuitively	739
18W	Worked Examples: Analog \leftrightarrow Digital	745
18W.1	ADC	745
18W.2	Level translator	748
18W.3	Micro 6: Data Tables	975
19L	Digital Project Lab	749
19L.1	A digital project	749
19L.2	Task for SiLabs users: off	1009
Part VI	Microcontrollers	755
20N.1	Lab: Micro 6: Standalone Microcontroller	1012
20N	Microprocessors 1	757
20N.1	Microcomputer basics	757
20N.2	Elements of a minimal machine	760
20N.3	Which controller to use?	762
20N.4	Some possible justifications for the hard work of the big-board paths	764
20N.5	Rediscover the micro's control signals...	765
20N.6	Some specifics of our lab computer: big-board branch	771
20N.7	The first day on the SiLab branch	773
20N.8	AoE Reading	778

20L	Lab: Microprocessors 1	780
20L.1	Big-board Dallas microcomputer	780
20L.2	Install the GLUEPAL; wire it partially	781
20L.3	SiLabs 1: startup	792
20S	Supplementary Notes: Microprocessors 1	803
20S.1	PAL for microcomputers	803
20S.2	Note on SiLabs IDE	805
20W	Worked Examples: A Garden of Bugs	809
21N	Microprocessors 2. I/O, First Assembly Language	813
21N.1	What is assembly language? Why bother with it?	813
21N.2	Decoding, again	818
21N.3	Code to use the I/O hardware (big-board branch)	821
21N.4	Comparing assembly language with C code: keypad-to-display	824
21N.5	Subroutines: CALL	826
21N.6	Stretching operations to 16 bits	830
21N.7	AoE Reading	831
21L	Lab: Microprocessors 2	832
21L.1	Big-board: I/O. Introduction	832
21L.2	SiLabs 2: input; byte operations	844
21S	Supplementary Notes: 8051 Addressing Modes	857
21S.1	Getting familiar with the 8051's addressing modes	857
21S.2	Some 8051 addressing modes illustrated	867
22N	Micro 3: Bit Operations	869
22N.1	BIT operations	869
22N.2	Digression on conditional branching	874
22L	Lab Micro 3. Bit Operations; Timers	881
22L.1	Big-board lab. Bit operations; interrupt	881
22L.2	SiLabs 3: Timers; PWM; Comparator	886
22W	Worked Examples. Bit Operations: An Orgy of Error	901
22W.1	The problem	901
22W.2	Lots of poor, and one good, solutions	901
22W.3	Another way to implement this "Ready" key	904
23N	Micro 4: Interrupts; ADC and DAC	905
23N.1	Big ideas from last time	905
23N.2	Interrupts	906
23N.3	Interrupt handling in C	911
23N.4	Interfacing ADC and DAC to the micro	912

23N.5	Some details of the ADC/DAC labs	917
23N.6	Some suggested lab exercises, playing with ADC and DAC	921
1.2	Oscilloscope	1119
23L	Lab Micro 4. Interrupts; ADC and DAC	926
23L.1	ADC → DAC board	926
23L.2	SiLabs 4: Interrupt; DAC and ADC	931
1.6	Power supply	1121
23S	Supplementary Notes: Micro 4	1946
23S.1	Using the RIDE assembler/compiler and simulator	1946
23S.2	Debugging	1951
23S.3	Waveform processing	955
1.11	Wire	1122
24N	Micro 5. Moving Pointers, Serial Buses	959
24N.1	Moving pointers	959
24N.2	DPTR can be useful for SiLabs '410, too: tables	964
24N.3	End tests in table operations	964
24N.4	Some serial buses	966
24N.5	Readings	974
24L	Lab Micro 5. Moving Pointers, Serial Buses	975
24L.1	Data table; SPI bus; timers	976
24L.2	SiLabs 5: serial buses	982
24S	Supplementary Note: Dallas Program Loader	993
24S.1	Dallas downloader	993
24S.2	Hardware required	993
24S.3	Procedure to try the loader: two versions	994
24S.4	Debugging: LOADER420, in case you can't write to flash	999
24S.5	Debugging in case of trouble with COM port assignments	1000
24W	Worked Example: Table Copy, Four Ways	1003
24W.1	Several ways to copy a table	1003
25N	Micro 6: Data Tables	1006
25N.1	Input and output devices for a microcontroller	1006
25N.2	Task for big-board users: standalone micro	1008
25N.3	Task for SiLabs users: off-chip RAM	1009
25L	Lab: Micro 6: Standalone Microcontroller	1012
25L.1	Hardware alternatives: two ways to program the flash ROM	1012
25L.2	SiLabs 6: SPI RAM	1018
25L.3	Appendix: Program Listings	1021
26N	Project Possibilities: Toys in the Attic	1022
26N.1	One more microcontroller that may interest you	1023
26N.2	Projects: an invitation and a caution	1025
26N.3	Some pretty projects	1025

A	26N.4 Some other memorable projects	1030
	26N.5 Games	1041
	26N.6 Sensors, actuators, gadgets	1043
	26N.7 Stepper motor drive	1049
	26N.8 Project ideas	1051
	26N.9 Two programs that could be useful: LCD,Keypad	1052
	26N.10 And many examples are shown in AoE	1052
	26N.11 Now go forth	1052
B	A Logic Compiler or HDL: Verilog	1053
	A.1 The form of a Verilog file: design file	1053
	A.2 Schematics can help one to debug	1054
	A.3 The form of a Verilog file: simulation testbench	1055
	A.4 Self-checking testbench	1058
	A.5 Flip-flops in Verilog	1060
	A.6 Behavioral versus structural design description: easy versus hard	1064
	A.7 Verilog allows hierarchical designs	1065
	A.8 A BCD counter	1068
	A.9 Two alternative ways to instantiate a sub-module	1070
	A.10 State machines	1071
	A.11 An instance more appropriate to state form: a bus arbiter	1073
	A.12 Xilinx ISE offers to lead you by the hand	1076
	A.13 Blocking versus non-blocking assignments	1077
C	Using the Xilinx Logic Compiler	1080
	B.1 Xilinx, Verilog, and ABEL: an overview	1080
D	Transmission Lines	1089
	C.1 A topic we have dodged till now	1089
	C.2 A new case: transmission line	1090
	C.3 Reflections	1092
	C.4 But why do we care about reflections?	1094
	C.5 Transmission line effects for sinusoidal signals	1097
E	Scope Advice	1099
	D.1 What we don't intend to tell you	1099
	D.2 What we'd like to tell you	1099
F	Parts List	1105
G	The Big Picture	1113
	23N.1 Big ideas from last time	1113
	“Where Do I Go to Buy Electronic Goodies?”	1114
H	Programs Available on Website	1116

I Equipment	1119
I.1 Uses for This List	1119
I.2 Oscilloscope	1119
I.3 Function generator	1120
I.4 Powered breadboard	1120
I.5 Meters, VOM and DVM	1121
I.6 Power supply	1121
I.7 Logic probe	1121
I.8 Resistor substitution box	1121
I.9 PLD/FPGA programming pod	1122
I.10 Hand tools	1122
I.11 Wire	1122

J Pinouts	1123
J.1 Analog	1123
J.2 Digital	1125

Index	1128
--------------	------

Who's likely to enjoy this book and course

A day at a time: Notes, Lab, Problems, Supplements

You need not resemble the students who take our course at the university, but you may be interested to know who they are, since the course evolved with them in mind. We teach the course in three distinct forms. Most of our students take it during fall and spring daytime classes at the College. There, "subplementary notes" – lab exercises – are given to the students. We think that these notes will let you understand the circuits much better than the textbook does. A few cross-registered from MIT who need an introduction quicker (and less deep) than that supplied usually enjoy every minute of a weekly two-hour lab. Most of these courses offered down there. (We don't get EEs here, we get people who want to learn basics and circuit theory.) Most often, "supplementary notes," – for example, with notes on how to read less formal introductions to the subject. The last group will skip the note because they already understand the book. This is fine. That's just what we mean by "supplementary notes." It's sometimes the "box" is a lab setup (we get students from medical schools) or a control apparatus that the student would like to demystify.

In the summer version of the course, about half our students are rising high school seniors – and the ablest of these prove a point we've seen repeatedly: to learn circuit design you don't need to know any substantial amount of physics or sophisticated math. We see this in the College course, too, where some of our outstanding students have been Freshmen. Although most are at least two or three years older.

First, this book means to be self-sufficient. After all, we were to be the best. And we can't help boasting, as we did in the preface to the 1999 Student Manual, that once in a great while a professor takes our course, or at least sits in on it, and buttonholes one of us recently in a hallway, on a visit to the University where he was to give a talk. "Well, Tom," he says, "One of your students finally made it." He points to the young man in the audience, who has just won a Nobel Prize. We wish we could claim that we helped him get it. We can't. But we're happy to have him as a guest.

We expect that some of these visitors will notice a few things about our course. First, it's dense; your functions of first difference. We'll show you how to use it to analyze the behavior of a system. This was Frank Wilczek! He did sit quietly in the back of our class for a while, hoping for some insights into a simulation that he envisioned. If those insights came, they probably didn't come from us.