The Art of Scientific Discovery

3 credits

Tuesdays and Thursdays in BSW 510 from 14:00 to 15:15

A.T. Winfree, 326 or 372 BSW: 621-3495, -3144

winfree@email.arizona.edu

You should read this over every month during the course.

It also appears at my lab pages

Most students don't take it seriously at first.

You may need a reminder, or several.

Who: Undergrads including freshmen, grad students, and postdocs have enjoyed this course and claimed to benefit from their vigorous engagement in it. Younger students typically do better, perhaps due to their briefer exposure to the educational system. See comments at **the lab web pages**

What: The aim of this course is to develop your ability of solve problems like those encountered in scientific investigations. We examine how specific problems were solved in the past, examine 'inspirational readings', and tackle selected puzzles for pencil and paper and for simple lab manipulation. These exercises are intended as 'practice scrimmages' in strategy and tactics of recognizing ignorance, of posing questions, of cultivating multiple alternative solutions, of eliminating rejectable candidate solutions, of spotting and taking advantage of your own mistakes, and especially of learning a **positive attitude** toward mistakes, because they are often the most available doors to discovery.

These exercises depend as little as possible on knowledge of any particular subject area. That way everyone is on an equal footing of unfamiliarity and no one is likely to be deprived of exercise by already ‘knowing’ 'the' solution. The aim is to experience a feeling of disorientation and hopeless lost-ness, so you will learn not to despair in paralysis but instead focus on method, generate several alternative guesses, and test them for workability. Readings and examples are drawn from all the sciences, often emphasizing biology. The discovery exercises are mostly made from elementary mathematics so as to require no lab setup and so as to be comprehensible to students from diverse backgrounds. There are some hands-on lab-type exercises too. All are contrived much as the organizers of an Easter Egg Hunt do in the hour before little kids

arrive with their baskets: surprisingly many discoveries are rigged into these exercises for your gratification if you will but learn how to discover stuff.

This is **not** a lecture course. The objective is **not** to add to your store of useful facts. Nor will you be passively stuffed by the professor with sophistication and accordingly accredited. As in weight-lifting, you will benefit from this course in proportion to your investment of time and effort. Interactions with your peers in this gym are contrived to leave you with muscles and installed habits of exercise that will last a long time. **Remember the weight-lifting metaphor.** The purpose of making this a formal 'course' is to provide you a legitimate (regularly scheduled, graded) escape from the usual pressures, during which to consciously cultivate skills and personal style in problem solving. In this course actually solving the practice problems is way less important than learning how to **try** (and, for grading, **demonstrating** real effort.)

Some people suppose problem-solving cannot be taught. They suppose that you are born with innate ability or not, and that's all there is to it. In contrast, I think we are **all** born with it and mostly lose it during and because of schooling and the general intimidation that comes with any competitive society. We can refine and enhance it about as much as we please. One example: according to the Proceedings of US National Academy of Sciences in spring 2000, London taxi drivers develop bigger hippocampus (the part of the brain involved in navigation) the longer they work at that job.

Thinking styles differ immensely between individuals. Evidence: widespread disagreement about almost everything. Given persistent diversity of styles, it seems likely that some styles are better than others for different purposes or for different individuals. If so then by getting acquainted with alternative styles and by exercising some 'natural selection' between alternative styles during diverse exercises, you can prove to yourself that thinking **is** an improvable skill. In 'real life' we are so intent on getting immediate solutions to urgent hurtful problems that we seldom feel the leisure required to examine how we get them and how we fail to. While swimming with a goal in sight and a clock running, you don't feel free to experiment, for example, with breathing on the **other** side of your stroke. In this course you are free and even **compelled** to. There will be much choking and sputtering, but it's OK here because not much depends on finishing first within this one semester. We are trying to improve your whole future life.

Your Professor:

A.T. Winfree. See web site for supplementary info on the course and for the prof's resume.

We have three main tools in this course:

1) Readings:

Ehrlich (physicist) Nine Crazy Ideas in Science: A Few Might Even Be True

Adams (consulting engineer) Conceptual Blockbusting

And a lot of xeroxed handouts, not listed here, many from current periodicals. You will read these and comment on them, at least by underlining and making marginal notations. **I expect you to** commit to paper a page per class session to celebrate the best things you find or think of while involved with these readings.

If you will save a checklist of good ideas gleaned while reading (from the readings or from your own thoughts in reaction the readings) you can use this checklist to joggle your brains during every problem-solving session. It would be a good idea to put a check mark beside each such item when practiced, together with page number in your GamesWorth book (see below). See which ones help you.

By the way, so far as I am aware, no student has ever done this. I still recommend it. I am not going to play Big Brother in a effort to make sure you do this and other useful exercises. Your life is up to you.

2) Problems --- the equivalent of bar-bells for lifting --- for homework and for in-class collaboration to allow you to practice intellectual gimmicks suggested by the readings. Write down your approaches, your lucky insights, how you got into and out of blind alleys. **This** is the main thing, **not** the 'answers'. Keep a diary in your GamesWorth book (see below) to focus your mind on strategy and tactics, not just on the ostensible bottom line (which is **not** the bottom line in this peculiar course). The purpose of the puzzles (many of them silly) is to slow you down for a few minutes so you can examine the working of your own mind. It is hard to develop consciousness of how you do it, but awareness is the first step to correction and improvement of any skill. Contrary to widespread fiction, and **un**like watching your feet while dancing, it will **not** hobble you. Ask any gymnast about such matters.

Use these homework puzzles to nucleate a habit of doing a daily 'Game's-Worth' (henceforth, **"gw"**) of focused thought, as in the first hand-out (Platt: The Art of Creative Thinking: the allusion is to how much thought it takes to play one game of serious chess). This might be the most important (potentially enduring) effect of the course. I will examine your daily (or at least 5 times a week, realistically) GamesWorth notebook at the end of semester.

I **do** insist that you formally log your brains in and out of each session by numbering the pages used (so you can refer to them from elsewhere) and noting the date and start and end times. Also record **where** you are working: the idea is to find the place that works best. You are to write only on the right side pages of a

bound (not-looseleaf) notebook. When you peruse your neighbor's gw, remind him/her to do all this. You will find that all this is not just busywork.

At the end of each session, before you log out, you are to tidily summarize, as though for notarizing in an industrial research lab (but really so your classmates can read it and glean the same harvest as you did.) There being 15 weeks * 5 = 75 days in the semester, you will need at least 150 pages (times 2 because there is also a left side) for thinking and summarizing. Likely this will require **two** such notebooks.

What are the **left** sides for? (meaning, the backside of each sheet of paper, on the left when the gw book is open before you, not meaning the left half of each side of paper). For two things:

a) In-class notes

b) Re-considering your prior thinking. This Monday-morning quarterbacking or morning-after reconsideration is to be done much later, after you have disengaged from the details and engaged other problems. Then you can look back and sense where you **could** have taken a different approach, see how well the methods you are trying did in fact work out for you, see what alternative discoveries you might have made (e.g., the ones your classmates did) and why you didn't. After the first few weeks I expect you to discipline yourself from time to time to do such a "morning-after" re-examination of some problem you struggled with weeks earlier. See how your perspective has changed. See how differently you would tackle it now. See why you got stuck before or why you went straight to a nifty solution without tripping over the obstacles everyone else did. We are here not so much to solve the problems as to see how we didn't or see how some quirky habit of thought saved the day, and benefit from those recognitions. This requires morning-afters. A thoughtful thorough morning-after is a perfectly valid substitute for working a new problem in your gw notebook. This content might become its principal value.

My own idea of a gw goes along with feelings of quiet, freedom from distraction, etc., thus necessarily away from people, TV, and music (which completely takes over my cerebral processors.) I need a big open space that becomes littered with drawings and with verbal notes, usually in outline form, and with stacks of worked-out simple examples. Not everyone works best this way. Some people think productively only in dialogue with a partner. Others only in a coffee shop. If you are that kind, do it that way. An important part of the semester's experience is to try a few different ways, find a best one for you, and stick to it habitually: log in and out at that place and time each time, many times in a row.

Your gw book is to be **bound** (at least by a wire helix) and even though it contains all your "scrap" "preliminary" work, should be legible like an industrial research notebook, as though to be notarized at intervals: **not** a collection of scraps. The idea is to make it

possible to resume work after an interruption, without having to start all over by rummaging a confused jumble. **No loose pages**. Don't forget to number the right-hand pages so you can say "... go to page xxx", "..continued from page...", etc. **Succinctly rewrite the essentials of your work before finishing for the day.**

Keep the readings (plus whatever other pertinent stuff you might encounter elsewhere during the semester) in a separate **loose-leaf binder** (not interleaved like a bookmark ready to fall out when you open your notebook, and not in a bulging paper pocket stuffed with disorderly sheets), together with your extractions from them or comments on them: As noted under resource (1) above, **I expect to see** a page of cogent thought, besides marginal scribbles and under-linings, on each.

So: a bound notebook, and a loose-leaf binder for hole-punched handouts.

3) The genetic diversity and diversity of life-experiences and habits of thought that we collectively bring to the table. There will be daily swapping of gw's so that you can benefit from your peers' perspectives and share in their harvest of insights (supposing you all discipline yourselves to make these fruits plainly accessible). This will also keep you on your toes, unless you enjoy being not-understood or being the one to come empty-handed.

You have plenty of opportunity ahead of you in daily gws at home for practicing solo thinking skills. But don't neglect to also work together if you want to: dual GamesWorths often work pretty well, like cutting wood with a long 2-handled band saw. Note your partner's name and contributions, along with your log-in and log-out times.

During class we also practice aggregate thinking skills, i.e., braving social opprobrium by blurting out nutty ideas, and risking devastating counter-attack by publicly objecting to nonsense blurted by others. Even though first notions seldom seem presentable, they are essential seeds to catalyze the next refinement. You must learn to do all parts of the process, not only by echoing within the confines of one skull, but also in the public forum. Class meetings will also prove essential for some problems in which no one individual can collect enough data, but if we pool data, reality will come into focus.

Grades:

Such a course should **not** be grade-oriented, but the institution **is** grade-oriented. While under 'pressure' of grades in other courses you might think you have to give this training short shrift 'just temporarily,' but then you will find yourself backlogged and despairing. Same as in athletics: it is vital to keep the daily habit.

Worse, if you don't make use of your opportunities in this course and bring contributions of thought to each class meeting, you dampen the spirit of the enterprise. Who wants to

work hard at crystallizing a clear insight to share, then swap gw notebooks in class, and receive a muddle in exchange?

I accordingly provide countervailing pressure in the form of a daily quiz in a blue exam book, besides paying attention to your contributions in class and by email after class. This also provides me an attendance record. (If you arrive too late for the warm-up quiz, log into the blue book anyhow, noting the time.) I will collect the blue books daily at the end of class.

I also want an email from you (to winfree @ email. arizona.edu) after **each** class session telling me in a couple lines, no more, **why** either your gw or the one you received in swap during the class meeting was the better of the two. The aim is that you should pay attention to alternative ways of thinking, evaluate them daily, and use some of them. And having others evaluate yours daily gives a little extra motivation to have something presentable in clear order for this show-and-tell.

On the last class day I will collect all gw books (**don't lose yours!**) to skim through, just to see if I generally agree with the impression given by emails from daily swaps. I will pay particular attention to stuff on the left-hand sides: your Morning-afters and your daily (signed) insightful and helpful comments on your classmates' recent work.

Your semester letter-grade will be based on those evidences according to a formula in my Excel spreadsheet for grading. If without fail you give this project a securely uninterrupted hour each day outside of class (ideally at the same daily hour 7x; if you feel that weekends are exempt from disciplined effort, then do a specially fine job on weekdays; BTW, hardly anyone actually does this, whatever good intentions they may have resolved on the first day) and participate vigorously and fairly in each of the 30 sessions, then you will likely develop an A.

It is a dread fact of history that whatever their expressed intentions at the outset, all but a few students each semester neglect the daily GamesWorth discipline and so find themselves short of ideas, insights, perceptions, and the corresponding intellectual gratifications, so about half the class ends up with a B, and a few flagrant goof-offs receive their customary lower grades.

Caution:

In almost every semester someone, unpredictably, really takes this experience to heart: chews at the problems like a dog with a leather bone, making mock attacks from every direction, **actually using** the many diverse approaches suggested in the readings. She maybe still fails to solve a lot of practice problems or even most of them, but makes stubborn and resourceful attempts, thinks about the readings and expands upon them in her GamesWorth book, develops real skill in problem solving, occasionally comes up with alternative solutions the professor never thought of, and leaves the course in high

excitement. Having seen how people **can** engage the course, your professor inevitably sets a high standard for grading ...

Your grade will come from my spreadsheet formula combining:

1) Lively participation **every** time (except dire emergency, with advance notice by email)

2) Performance on daily warm-up exercise in blue books

3) Daily email reports comparing two gw's … and if you like I will peruse your gw notebook at any time to see how active you have been, and especially to spot-check your left-side morning-afters. BTW in comparing gw's please make a firm decision: do not cop out by reporting a "tie". And avoid 3-way swaps, please: I want to see the extent to which the two participants in each match agree about whose play was better. No more than one 3-way is needed, and that only on days with an odd number of participants.

4) My perusal of your gw book with emphasis on "Morning-after"s, and of others' gw books with emphasis on your insightful and helpful comments on that work

5) Your reading assigned materials **no later than** the corresponding class meeting date (see schedule below). Other than the Adams and Ehrlich books, I will get the readings to you a week before.

6) Grad students and Honors students must turn in some extra work as described below.

The Final Exam will be scheduled for in exam week at the usual class time. It will be a collection of problems from which you will choose some, exhibit as many distinct approaches as you can, and as many cross-checking distinct solutions as you can. All the problems we do solo and as a group during the semester may be regarded as sample practice problems for this Final Exam. At this moment I think this is best done as a take-home, rather than under time pressure: I'll ask your views as the time draws near.

Honors students (479H) are additionally required to visit the History of Science shelves in the library (and/or corresponding web sites), and get acquainted with some episode, and write up a clear analysis of how some discovery or discoveries came about, and some other ways they might have come about. I want some attention to mistakes and dead ends and how the investigators recovered from them. And a paragraph at the end declaring whether this is a closed case, or only the beginning of something more that did or might grow from it. I will hold you to a higher-than-undergraduate standard of English writing. 479-non-H students are also free to do this for extra credit.

Graduate students (579) are required to do as Honors students and additionally to provide a new exercise for next year's course. This should be an intriguing problem that can be understood with minimal background and can be solved with minimal specialized techniques other than ingenuity and meticulous care. The writeup should display a variety of ways to solve it, mentioning pitfalls of each and showing ways to check and cross-check every part of the solutions. Hide as many Easter-eggs as you can. Booby-traps are also fun.

Audits: No. There is nothing to audit (no lectures). Imagine auditing dance or debate or weight-lifting without full participation: not much point, right? Besides, with-holding the commitment that goes along with 'really taking the course', auditors (almost by definition, just 'hearing' the course) have chosen to respond preferentially to the inevitable pressures of **other** commitments than this one, and come to our practice scrimmages wearing white gloves, benefiting nothing from that waste of time. **You benefit from lifting weights only by lifting them, not by watching others.** No exceptions. (BTW there is always one ostensible student who gives every appearance of merely auditing, though apparently expecting a grade for it. Don't let it be you.)

Remember, most of the work will be done on your own or with someone in the class with whom you find it fun to ping-pong ideas: active involvement is essential. **Leave now** if you are unmotivated, just passively expecting to have your strings pulled. We will meet twice a week mainly to exchange information, to compare notes not really on the homework puzzles themselves so much as on **the approaches tried**, and to work jointly for a while on bigger problems or puzzles that need a little equipment or need more diversity of approaches and crazy suggestions or need lots of data-collecting, best pooled from many sources. The effect will presumably be that in real life afterwards you will think of lots of approaches, some of them successful, **before** launching yourself into the hopeless futility of the first that came to mind..

Notice the big problem that **only you can solve:**

In this course you are expected to act like an independent self-motivated creative individual. Our aim is enhance your creativity and curiosity and the satisfaction you can secure by solving mysteries in your own unique ways. You are to explore crazy new unfamiliar ways most of which won't be productive for you. But you don't know which ones. This course lifts the pressure so you can find out. This requires joyful playfulness, not grim determination. It seems incompatible with deadline pressure. So here is the **problem**: since you **are** under such pressure from elsewhere, you might procrastinate things not backed by pressure. Then you have to attempt them under time pressure later, and so not very creatively, not playfully, learning nothing from the experience. Hurrying under pressure is guaranteed to abort the special opportunities you confront in this course. So form the GamesWorth habit immediately and don't let it slip for any 'reason'. Remember that in such efforts an hour's work punctuated with three 5-minute interruptions has lost you not 15 minutes, as might be the case were you shining shoes

or digging a ditch: it has instead prevented you getting warmed up to 60-minute heat, replacing that experience by 3 times getting up to 15-minute heat. You can probably think of other experiences like this. Reserve that sacred daily uninterrupted hour to yourself (or self and partner, if you need to talk to think).

Readings to ponder **before** the class meeting (It's hard to catch up so don't fall behind!)

Two required books await you in the local bookstores:

J. Adams (consulting engineer) Conceptual Blockbusting

R. Ehrlich (physicist) Nine Crazy Ideas in Science: A Few Might Even Be True

Another is out of print: so I will provide Xerox, *.pdf, or text files
H. Judson (historian) Search for Solutions also in Main Libe Reserve
And lots of single short articles from here and there.

W.I.B. Beveridge (British MD) The Art of Scientific Investigation 1950 is not required this semester because I find that no one reads it anyhow, I think because archaic attitudes offend. I consider it the best of the lot and have placed it on Main Library Reserve and made it available on my web site as *.pdf files.

Other Good Books on reserve for your attention if you consider it important to acquire better skills in problem solving:

George Polya Induction and Analogy in Mathematics and Patterns of Plausible Inference, using elementary math as example material for general principles

James Gleick Genius biography of Richard Feynman, a great problem solver

Arthus Koestler The Watershed biography of Johannes Kepler (a chapter of "The Sleepwalkers")

Students requiring accommodation in testing or notetaking must notify me and must (within the first few days) bring a letter of certification from the Disability Resource Center.

The following is a retrospective syllabus of Spring 2001, with dates changed to reflect the future, but not intended as a strict preview of Fall 2001 because the course sharply evolves after each semester's student critiques, and also adapts to the particular assortment of student backgrounds in each new semester.

Readings and solo exercises are due for discussion of finished results on the date indicated; they were handed out a week in advance of that date (except for the first few). Group "lab" exercises are indicated here on the day they begin in class. In other words the syllabus tells the dates things are scheduled for in class, but most of your work was in the prior week.

01: Tues 21 Aug: Introduction, handouts

Adams preface and Chapter 1

Demonstrating the need: triangle problem

First of two contrasting challenges: 13 nails problem

(alternatively, the celts problem)

Section 1: Five sessions of Detecting Nonsense, Error Checking, False Assumptions, Cherishing Mistakes

02: Thur 23 Aug: Adams preface and Chapter 1

Platt: The Art of Creative Thinking

Feynman: Cargo Cult

Second of two contrasting challenges: conscious machines

03: Tues 28 Aug: Judson Chapter 1: The Rage

discuss Square Windows solo problem

04: Thur 30 Aug: Golden tooth: facts before explanations of facts

Salvation of Doug

Bookworm's journey

distinguishing things we know vs only imagine

05: Tues 4 Sep: N-Rays

Pathological Science

discuss phone cord problem

discuss Stockholm restrooms

06: Thur 6 Sep: Packet of readings: Valuing mistakes

Ehrlich Chapter 1 (Introduction)

some ways to check for errors

hidden assumptions

what is “understand” ?

Evaporated Gold

start group effort on Collective Reproduction

Section 2: Six sessions of Creative Blocks

07: Tues 11 Sep: Adams Chapter 2: Perceptual blocks

discuss Weird Organism

discuss Rearranged Triangle

start group lab on Dominoes

08: Thur 13 Sep: Barometer Story

Adams Chapter 3: Emotional Blocks

discuss Telltale Number

about assumptions and tying knots

09: Tues 18 Sep: Adams 4: Cultural blocks

Platt: Diversity

discuss Mercury’s mysterious hidden hemisphere

10: Thur 20 Sep: Adams 5: Intellectual blocks

taboo questions

Paths through mazes

11: Tues 25 Sep: Adams 7: Blockbusters

` Walking through walls

12: Thur 27 Sep: Dyson: Unfashionable

Capecci 1-page bio

Narlikar on Venture Funding

Sums of integers: like a jig-saw puzzle of cross-checks

Pedestrian Crosswalk mystery (lab)

Section 3: Six sessions of Observations and Questions

13: Tues 2 Oct: discuss Ant Walk and Seven Bridges

discuss observations outdoors on Pedestrian Crosswalk

start lab exercise on chemical pattern-formation

14: Thur 4 Oct: Judson 4: Chance

Anderson on research strategy

more chemical observations

discuss what isn't there (Surprisingly Hard)

15: Tues 09 Oct: Judson 8: Evidence

Mother Nature as magician; hallucinations

last chemical observations

discuss Rainbow Moon

16: Thur 11 Oct: Ehrlich Chapter 2

discuss Hairy People, Green Stars, and Escher Print Gallery

17: Tues 16 Oct: Ehrlich Chapter 3

discuss Zygotes

discuss Martian HoneyCombs

Spring break

18: Thur 18 Oct: Ehrlich Chapter 4

discuss Cevians

discuss Superposed filters

Section 4: Six sessions of Patterns, Empirical Generalizations

19: Tues 23 Oct: Judson 2: Pattern

discuss Presidents and States

discuss n dots on rim of circle, connected to slice the disk

20: Thur 25 Oct: Ehrlich Chapter 5

start Cell Shapes lab in class

21: Tues 30 Oct: Ehrlich Chapter 6

collaborative experiments on Cell Shapes

deal with Paired Observations

deal with Neutrinos

22: Thur 01 Nov: Adams 6: Alternative thinking languages

further experiments on cell shapes

do Egg Pouches lab in class

deal with Platonic Solids and applications

23: Tues 06 Nov: Ehrlich Chapter 7

Play Eleusis in class

deal with the Mirror Mystery

24: Thur 08 Nov: Ehrlich Chapter 10

start Stacked Cantilevers lab

Section 5: Six sessions of Inferences, Hypotheses, Explanations

25: Tues 13 Nov: Chamberlin: Multiple Working Hypotheses

further collaborations on Stacked Cantilevers

26: Thurs 15 Nov: **TBA**

theory of stacking cantilevers, resolution of wagers

deal with summing a series

deal with stalactites

27: Tues 20 Nov: Platt: Strong Inference

start LoShu lab experiments in class

Thanksgiving Break

28: Tues 27 Nov: Judson 7: Strong predictions

deal with The Miracle of FujiYama

finish complete theory of LoShu

` start discovering laws of toy universe in class

29: Thur 29 Nov: Feynman: Character of Physical Law

deal with Antigen Invasions

deal with Martian DNA

finish collaborative discovery of The Laws

All GamesWorth books collected for inspection

30: Tues 4 Dec: Judson 9: Theory

deal with Bacterial Hybrids

Final exam is scheduled in ?on Tue ? Dec, 2-4 PM