Supplemental Material

CBE—Life Sciences Education

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Introductory Statement: When a student begins their first attempt to pass the verbal final exam the instructor reads aloud an introductory/explanatory statement. It is as follows:

> This is the verbal final exam for the course. It is worth the same number of points as the course's regular written final exam. If, after many attempts, you eventually persevere and pass the test, you then earn a perfect score, a 100%, on the final exam for the class. If on the other hand, you eventually grow tired of taking the verbal final exam, you can always take the regular written exam during finals week, this has no impact on that whatsoever. Since you earn a perfect score for passing the exam, your performance in order to pass must be near perfect. Given that no one can be perfect at any moment of time, we have a system to accommodate this; it's called three strikes you are out. A strike occurs if you get something wrong, but on your own or with hints from me you are able to correct it. If you can correct yourself then you can continue all the way to the end and pass. Even if this occurs a second time, you get something wrong initially but eventually correct yourself; you still can continue to the end and pass. Only if that occurs a third time, i.e. you get a third strike, even if you are able to correct yourself, we just stop the exam right there and schedule another appointment. On a related matter, if you get something wrong that I consider significant, and are unable to correct yourself, then we will stop the exam right then and reschedule another attempt. And finally, you are limited to 60 minutes. The time is [ ] and in one hour if we are still talking about light reactions we will just stop right then and reschedule another appointment.

Phase 1: Explanation of Process of Photosynthesis
(i) Light Reactions: The first phase of the exam is designed to require the student to draw and explain the light reactions of photosynthesis (even if they explained it well at a previous appointment). At the start of the official exam time period the student is told to take their time and draw an illustration of the photosystems and carriers etc important for light reactions. This illustration serves as an aid so they have a drawing to use as they explain light reactions. When ready the instructor says: OK tell me how light reactions work. After the student is done explaining light reactions the instructor asks questions, first about whatever the student said that might not have been completely clear or accurate, then to determine the depth of student understanding, probing questions, for example: What is an absorption spectrum? How do the pigments absorb light in a photosystem? Why does a pigment prefer certain colors of light? How are electrons and orbitals involved? Where are we located anatomically in the cell/leaf? If we had 100 protons in the stroma and 200 in the lumen how much ATP do you predict we can make? What do you predict would happen if we put a hole in the membrane?

When the student successfully completes the light reactions they are then told of any strikes (significant errors) they may have accrued. If they have fewer than three strikes and time remains in the hour, they may proceed.

(ii) Calvin cycle: The instructor asks them to begin the next phase. They are told to draw and then explain the Calvin cycle including names of enzymatic and structural compounds. When the student is done explaining the process, once again the instructor asks questions to clarify, check errors and omissions, and then follow with probing questions, e.g. What are the names of phases and why? What is reduction? What would

happen if we only fixed 1 CO_2 molecule? What does G3P taste like and why does that makes sense from an evolutionary perspective?

If the student successfully completes the discussion of the Calvin cycle they are then told of any additional strikes they may have accrued. As was the case before, if they have fewer than three strikes and time remains in the hour, they may proceed. The instructor asks them to begin the next phase. As a somewhat contrived transition we routinely state: OK, let's pretend the glucose you just made in the Calvin cycle turns into a donut. Preferably a warm Krispy Kreme original glazed donut. Now let's discuss its digestion and absorption.

Phase 2: Explanation of the process of Digestion and Absorption
(i) Digestion and absorption of macromolecules: In the second phase the student is asked to explain digestion and absorption. We require them to know a sample set of organs and their function (oral cavity, stomach, small intestine, liver, gall bladder and pancreas, as well as a set of events; organ function, relevant cells, relevant enzymes, hormones, processes) but for efficiency sake we often instruct them to: Eat the donut and explain to me how digestion works in organ X, or alternatively, Eat the donut and explain to me how food group X is digested and absorbed. We have found that by randomizing which organ they are asked to discuss, like oral cavity, stomach, or pancreas; as well as which type of foodstuff or macromolecule, like fats, proteins or carbohydrates; students prepare for all questions. When the student has completed their initial explanation of digestion the instructor may ask questions for clarification, errors and omission but does not probe the organ level of this topic deeply. Instead the instructor asks the student to then focus on cell biology. Our goal is to more quickly get to the topics of membrane transporters, gradients and enzymes in the domain of cell biology using the parietal cell and/or the villus epithelial cell as models in context.

(ii) Parietal or villus cell biology: In this section of the digestion phase we probe a student's understanding of how a cell works and to make predictions about how membrane transporters and chemical reactions will respond to perturbations. For example we will ask a student to draw a stomach's parietal cell and explain how it makes HCl or to draw the small intestine's villus epithelial cell and explain how it absorbs glucose. We evaluate their explanation and probe for understanding with questions like, what would happen to this process in the parietal cell if a drug inhibited the enzyme carbonic anhydrase? Indicate which reaction rates would change by placing a check mark next to its arrow in your drawing, how might that change the pH in the stomach lumen or the bloodstream? Similar transporter questions can be used for the villus epithelial cell, e.g. What would happen if a drug inhibited the Na/K-pump? How would this affect other transporters? How would this effect the membrane potential? How would this effect the rate of glucose absorption/uptake? We can vary and reverse these questions for different students as well as the same student at different appointments by first asking what might happen if the membrane potential is changed.

As a final transition to the last phase of the test we request the student tell us some detail of the path an absorbed macromolecule, like glucose, must take to travel from a capillary

at the basolateral side of the villus cell to a capillary beside a beta cell in the pancreas. The student is expected to name some basic vessels and the path valves/chambers through the heart. We often request they do it without an illustration if possible. When the student is done we ask only questions if errors or omissions occurred, otherwise we talk about the last steps where glucose exits the capillary and enters the beta cells. We probe for understanding of diffusion via questions like: How does glucose exit the capillary as well as into the pancreatic cell?, Does it need a carrier or channel or something?, Why does it move?, What drives it?, Why do you predict this would occur?

Phase 3: Central Dogma -Biosynthesis of Insulin

(i) Biosynthesis of a secreted protein: The last phase of the verbal final exam requires the student to explain central dogma using the biosynthesis of a particular protein. We discuss insulin biosynthesis frequently in class so that is often what's initially asked. Students are required to draw a eukaryotic cell and explain the processes of transcription, translation and biosynthesis in terms of steps that occur at each organelle. Expectations are that they do it well but more in overview with only select points of high detail. They do not need to review every single step of initiation, elongation, termination but more exhibit a holistic understanding. For example they often say things like: "Here in the nucleus on this chromosome is the insulin gene, these double strands will be separated by the RNA polymerase and a single strand hnRNA will be created. Then during processing introns will be spliced out by spliceosomes and the exons glued together. Next a polyA tail and GTP cap will be added to protect the mRNA from enzymes and help the nuclear pore and ribosome know where the 5' and 3' ends are. . ." When the student has completed their explanation of insulin biosynthesis and secretion, we ask follow-up questions for clarity, errors, omissions and the probe with queries like: What if there's a mutation? What do you predict would happen if we add some hydrophobic domains to the gene?

(ii) Biosynthesis of other proteins: After the student shows an acceptable understanding of how insulin is created, we ask what path would be taken in the biosynthesis of an apical channel protein (like CFTR), or a cytoplasmic protein (like tubulin). We also often ask the student to draw an enlarged transport vesicle and indicate in blue ink where insulin might be found, what if the CFTR channel protein was also in the same vesicle, add it with red ink to the drawing. We also then ask that they create illustrations to show how they predict the vesicle would behave when it reached the cell membrane.

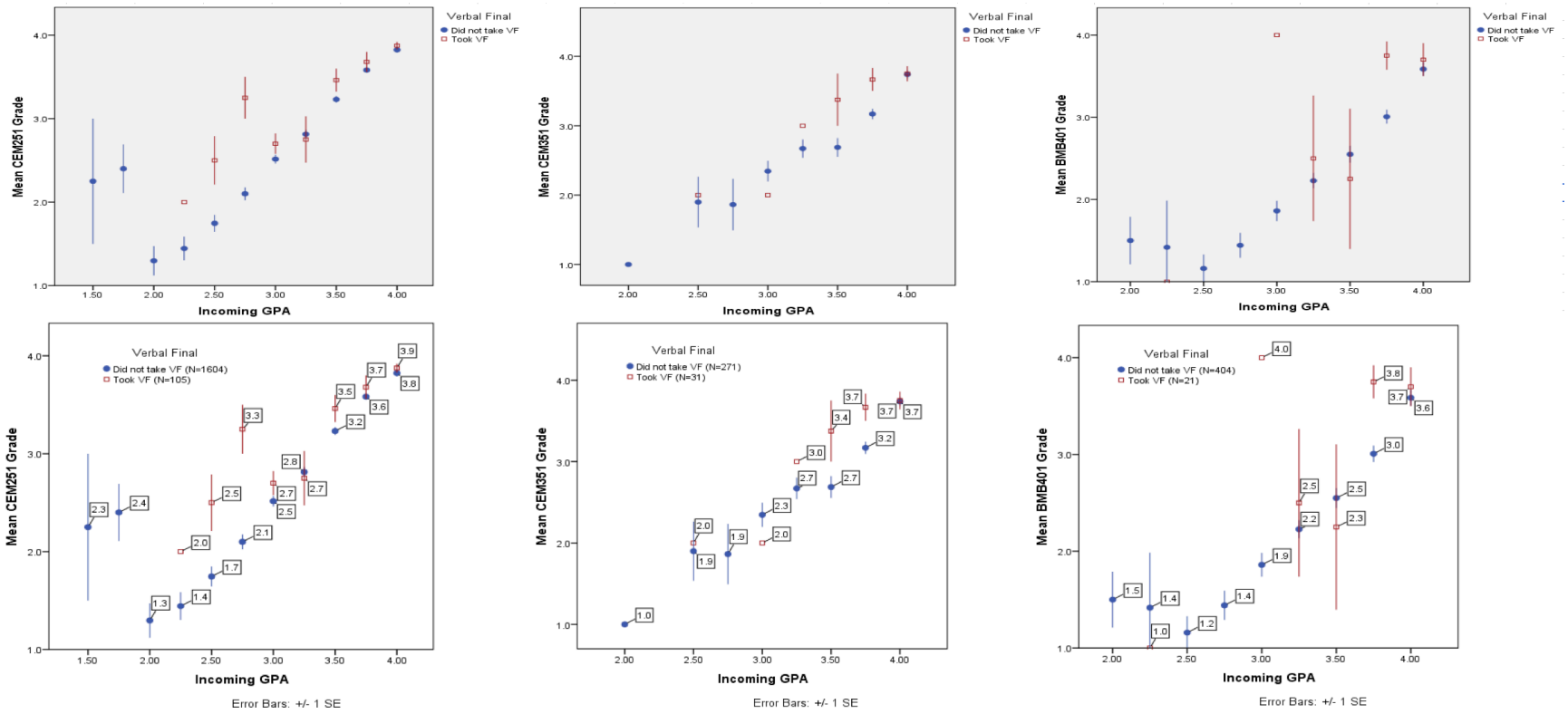

Figure S1. Performance differences in upper-level science courses between students who passed the verbal final ("Took VF" red squares) and matched peers in the same major. Database included student records of performance in upper level classes during the time period from 1997 to 2010. Two representations of average course GPA in (**left panels**) CEM251 (Organic Chemistry), (**center panels**) CEM351 (Advanced Organic Chemistry), and (**right panels**) BMB401 (Basic Biochemistry). Out of the twelve courses analyzed, CEM 351 was the only course where linear modeling showed *Verbal Final* as a significant variable, where those who took the final received 0.368 of a grade higher than those who did not (β=0.115). Some of the remaining courses showed visual evidence of greater performance by verbal final takers (BMB 401 and CEM 251), but this was not supported by the linear modeling as in CEM 351."

Supplemental Table S1: Average grade in course of students who passed the Verbal Final exam (Passed VF) are compared to matched peers who did not participate or pass (control). All students in the table took the same 100-level introductory biology courses during semester when VF exams were offered with the same instructor. Below is a representation of the performance of the two cohorts in higher-level STEM classes. Comparisons are divided into each quartile by performance on ACT exam (N=number of students in sample, S.D. is standard deviation, #4=top quartile). Acronyms: Chemistry (CEM), Biochemistry (BMB), Physiology (PSL), Microbiology (MMG), Zoology (ZOL).

Quartile			ZOL341	PSL431	PSL432	CEM251	CEM252	CEM351	CEM352	BMB401	BMB461	BMB462	MMG301
1	Control	Mean	2.47	2.130	2.341	2.50	2.39	2.833	2.900	1.56	2.323	2.250	2.47
		N	32	27	22	52	47	6	5	9	31	30	18
		S.D.	.906	1.1815	1.1061	.970	1.175	.8756	1.3416	1.044	.8119	.8174	.899
	Passed VF	Mean	3.20	2.500	2.200	3.04	3.17	3.000	3.000	2.00	2.813	2.625	2.67
		N	5	5	5	12	12	1	1	3	8	8	6
		S.D.	.570	1.0607	1.2550	.811	.888			2.000	.7990	.6944	.876
	Total	Mean	2.57	2.188	2.315	2.60	2.55	2.857	2.917	1.67	2.423	2.329	2.52
		N	37	32	27	64	59	7	6	12	39	38	24
		S.D.	.899	1.1553	1.1107	.960	1.159	.8018	1.2007	1.249	.8235	.7993	.878
2	Control	Mean	2.84	2.417	2.324	2.86	2.88	3.250	4.000	2.44	2.559	2.615	2.57
		N	16	18	17	42	41	2	1	9	17	13	14
		S.D.	.870	.9587	1.2112	1.002	1.100	1.0607		.982	.9334	.8697	1.158
	Passed VF	Mean	3.28	2.577	3.045	3.25	3.16	3.500	2.750	3.75	3.214	2.917	2.39
		N	9	13	11	18	16	2	2	2	14	12	9
		S.D.	.667	1.3361	.8202	1.088	1.207	.7071	1.0607	.354	.5447	.5573	.993
	Total	Mean	3.00	2.484	2.607	2.98	2.96	3.375	3.167	2.68	2.855	2.760	2.50
		N	25	31	28	60	57	4	3	11	31	25	23
		S.D.	.816	1.1142	1.1169	1.035	1.127	.7500	1.0408	1.031	.8386	.7377	1.077
3	Control	Mean	3.05	2.821	2.808	3.04	3.04	2.667	1.750	2.14	2.429	2.750	2.82
		N	21	14	13	39	34	3	2	7	21	14	11
		S.D.	.757	1.0489	1.0316	.756	.829	.2887	1.0607	.690	1.1650	.8026	.603
	Passed VF	Mean	3.05	2.571	2.571	3.68	3.43	3.500	3.300	3.67	3.000	2.818	2.75
		N	10	7	7	17	15	3	5	3	12	11	6
		S.D.	.985	1.2392	1.4557	.498	.923	.8660	.9747	.577	.7687	1.0313	1.440
	Total	Mean	3.05	2.738	2.725	3.23	3.16	3.083	2.857	2.60	2.636	2.780	2.79
		N	31	21	20	56	49	6	7	10	33	25	17
		S.D.	.820	1.0911	1.1639	.744	.868	.7360	1.1802	.966	1.0627	.8907	.936

4	Control	Mean	3.18	2.300	2.067	3.20	3.10	3.333	3.417	2.72	2.650	2.462	3.04
		N	19	15	15	32	31	12	12	9	20	13	12
		S.D.	1.083	.9024	1.3211	.694	.860	.6513	.8483	.833	.8288	.8530	.753
	Passed VF	Mean	3.43	3.286	3.000	3.67	3.74	3.889	3.722	3.30	3.269	3.278	3.00
		N	14	7	7	18	17	9	9	5	13	9	8
		S.D.	.584	.9063	1.2583	.728	.400	.2205	.5652	.837	.5991	.7546	.756
	Total	Mean	3.29	2.614	2.364	3.37	3.32	3.571	3.548	2.93	2.894	2.795	3.03
		N	33	22	22	50	48	21	21	14	33	22	20
		S.D.	.902	.9992	1.3468	.734	.789	.5763	.7400	.852	.7980	.8952	.734
Total	Control	Mean	2.83	2.365	2.366	2.85	2.81	3.109	3.150	2.22	2.466	2.457	2.69
		N	88	74	67	165	153	23	20	34	89	70	55
		S.D.	.940	1.0608	1.1696	.916	1.056	.7223	1.0773	.978	.9256	.8373	.900
	Passed VF	Mean	3.26	2.719	2.783	3.44	3.39	3.700	3.441	3.15	3.106	2.913	2.69
		N	38	32	30	65	60	15	17	13	47	40	29
		S.D.	.714	1.1773	1.1498	.836	.907	.4928	.7682	1.197	.6671	.7835	.995
	Total	Mean	2.96	2.472	2.495	3.02	2.97	3.342	3.284	2.48	2.688	2.623	2.69
		N	126	106	97	230	213	38	37	47	136	110	84
		S.D.	.898	1.1037	1.1737	.930	1.047	.6985	.9468	1.113	.8964	.8437	.928

Supplemental Table 2: Exemplars of student feedback, which either support predictions made in educational literature, or alternatives, to how the verbal final exam increases student learning.

Support predictions in educational literature		Present alternatives to those in literature	
Subcategory description	**Evidence**	**Evidence**	**Subcategory description**
Students would increase their time-on-task	I think the optional verbal final greatly encourages students to study and learn more. The verbal final requires that you understand every concept back and forth, inside and out, and upside down. I have been studying diligently for the verbal final and if i do not pass i will do better on the actual final because i have such a deep understanding of the topic. The reason it helped me was not the actual verbal but the preparation involved for the exam. You don't know exactly what questions will be asked and to what detail each answer will go to. This made me explore each topic beyond just the basic answers and actually start looking to how things work and what else these things effect. By doing this, it really helps learning how everything I learned connects itself	Moreover, it really brings to light how interconnected the topics are that you spent all semester learning. If you aren't able to pass the verbal final, you are already set up for success on the traditional written exam because you have already studied everything in excess.	**Value of connecting different topics of the course**
Importance of overt verbalization	Speaking things aloud helps increase understanding because you have to formulate a logical argument in your mind and present it in a way that other people can understand. The verbal final exam option is good for student learning because if you can explain aloud everything you learned with little to no problems, then the professor and course has done its job and you learned everything that you were suppose to. Besides, this is better than a written final because it actually takes	I had to put so much effort into mastering all the material. In the end, when I passed, I felt like the course truly helped me gain so much knowledge. Getting your hand shaken by a professor for passing is incredible. It helped me a ton to be able to explain the topics to someone who could point out my discrepancies. Then I could go back, learn those topics better, and try once again to prove I knew the material. I am so happy that I passed as a traditional final	**Opportunity to work closely with a professor is associated with student success**

	remembering what you learned and applying it. I liked this option a lot because it forced me to study and understand all concepts and material on a fundamental and application level that let me answer questions I may not normally have known the answer to because I understood the biology in this critical way. I think the questions were thought provoking and required me to think and speak clearly in such a way that was both direct and detailed. This helped me with my verbal communication skills and analysis abilities.	does not help my learning in the least.	
Has positive effect for participants	I had to put so much effort into mastering all the material. In the end, when I passed, I felt like the course truly helped me gain so much knowledge. Getting your hand shaken by a professor for passing is incredible. I also learned a lot while taking the Verbal Final, as well as preparing for it. I wish every class did this. It really challenges students and requires them to know concepts in GREAT detail. the incentive for a 100% on the final PLUS not having to worry about the exam for finals week is a great plus. Verbal final is the best thing ever. I have never been in a class where I can say that I know the material and could teach it to anyone.	I'm sure it helps the majority of students, and I like the idea. Personally, I get very nervous giving presentations, etc. so I'm semi reluctant to take the verbal final. However, it is an excellent idea. I think the verbal final is beneficial for students, the only thing I would change is scheduling and availability because due to my complex schedule I was unable to take the verbal final. I think for students that do not need things written down and can remember things off the top of their head, this is a wonderful idea, but for those of us that are not able to do that so easily, the option of a verbal final isn't very appealing.	**Has positive effect for more than participants**