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EDUCATIONAL NEWS REPORT

Electron flow from water to NADP+ with students acting as molecules in the chain: a Z-scheme drama in a classroom

Sagarika Jaiswal[1] · Misha Bansal[1] · Shirshanya Roy[1] · Adyasha Bharati[1] · Barnali Padhi[1]

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Introduction: background

In oxygenic photosynthesis, water is oxidized to molecular oxygen and four electrons from it are transferred, via two pigment systems, using two light reactions, to produce two molecules of NADPH (reduced nicotinamide adenine dinucleotide phosphate); this is what is known as the Z-scheme of photosynthesis. In this educational report, we describe how Govindjee explained the concepts of excitation of reaction center chlorophyll *a* molecules, redox potential, and downhill electron transfer by having students play the role of different molecules in the electron transfer chain in an auditorium with ascending steps. In addition, the concept of oxygen evolution in four steps, that of two electron gate, the role of bicarbonate in it, action of how the herbicide diuron functions, and how the system can be made to produce hydrogen instead of carbohydrate was explained. All of this can be accomplished within 20–25 min, leaving ample time for discussion: questions and answers.

In order to appreciate, understand and implement the Z-scheme drama, a background information on "*Oxygenic Photosynthesis*" is essential; it begins with light absorption in two different photosystems: Photosystem I (PSI) and Photosystem II (PSII), the former leading to NADP reduction, and the latter leading to water oxidation (Rabinowitch and Govindjee 1969; Blankenship 2014; see Fig. 1a). In each system, light is absorbed by pigments in their antenna complexes which then leads to excitation energy migration and transfer to the reaction center chlorophylls: P700 and P680. (For a review of the primary processes, see Mircovic et al. 2016.) It is here that light energy, in the form of excitonic energy, is converted to chemical energy with very high (almost 95 %) efficiency. In PS II, water is ultimately oxidized to molecular oxygen, and plastoquinone is reduced; thus, it acts as water-plastoquinone oxido-reductase. Plastoquinol delivers its electrons via cytochrome (Cyt) b6/f complex ultimately to plastocyanin; thus, Cyt b6f acts as a plastoquinol–plastocyanin oxidoreductase. On the other hand PSI oxidizes reduced plastocyanin and reduces $NADP^+$ to NADPH; thus, PSI acts as plastocyanin-NADP oxidoreductase. During this process, and by the action of what is called a "Q"-cycle, protons are transferred from the stroma of the

This News Report was read and edited by **Thomas D. Sharkey**, of the Editorial Board of Photosynthesis Research. It was accepted with the following comment: "This report of a play staged by students under the direction of Govindjee (Urbana, Illinois, USA) and B C. Tripathy (New Delhi, India) shows how a long interest of Govindjee (acting out photosynthesis) can be carried out in a modern lecture hall. It incorporates active learning, group exercise, and would appeal to students with varied learning styles. I hope it stimulates others to undertake what should be an enlightening and fun experience for students".

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✉ Barnali Padhi
padhi_barnali@yahoo.in

Sagarika Jaiswal
sagarikajaiswal93@gmail.com

Misha Bansal
mishabansal94@yahoo.com

Shirshanya Roy
wrikster666@gmail.com

Adyasha Bharati
adyasha.bharati@gmail.com

[1] School of Life Sciences, Jawaharlal Nehru University, New Delhi 110067, India

thylakoid membrane to its lumen. Together with the energy from the membrane potential across the thylakoid membrane created due to charge separation across the thylakoid membrane, this proton gradient leads to ATP synthesis at the ATP synthase, as described by Peter Mitchell. The NADPH and ATP then provide all the energy needed to convert CO_2 into sugars by the Calvin-Benson-Bassham cycle. For a background, on CO_2 fixation including those in C4 plants, see Rabinowitch and Govindjee (1969), and Blankenship (2014). A pdf of a diagram of the entire "oxygenic photosynthesis" process, made by D. Shevela and Govindjee (unpublished; 2016), can be downloaded free from http://www.life.illinois.edu/govindjee and a full size poster printed for the class room. Further, a copy of the 2010 Z-scheme (by Wilbert Veit and Govindjee) of photosynthesis may be downloaded from http://www.life.illinois.edu/govindjee/2010_z-scheme.pdf; and its description by Govindjee and R. Govindjee is available at http://www.life.illinois.edu/govindjee/textzsch.htm. Mohapatra and Singh (2015) have also described the Z-scheme (see Fig. 1 there, reproduced here below as Fig. 1a) as well as the details of how Govindjee teaches the "Z-scheme" in an outdoor setting. We recommend it to all the readers of this article.

We must mention that a unique thing related to the teaching of Govindjee is his emphasis on the special role of bicarbonate, bound on the non-heme iron, between the primary and secondary plastoquinone Q_A and Q_B, as it acts to bring protons for the reduction of Q_B to Q_BH_2 (Shevela et al. 2012).

The Z-scheme drama in the class room

From the sun (that gives light) to NADP that is reduced to NADPH, the cast of characters included students in the class as well as our teachers (B.C. Tripathy as the Sun; and Govindjee as the bicarbonate ion). Footnote[1] gives the list of all the components and the names of those who acted for them; and Footnote[2] gives the order of appearance of the characters in the drama.

The setting

We were in an auditorium with benches arranged in an ascending fashion which we had taken advantage of in order to depict the energy levels of the Z-scheme intermediates (Fig. 1b; cf. Fig. 1a). All the molecules were placed in their positions according to their energy levels, following their locations as if they were in the thylakoid membrane. Red colored arrows were stuck to the seats to trace out the letter Z. Balloons, colored green, blue, yellow, and orange, served as the light harvesting complex (LHC I and LHC ll), the manganese complex, and the cytochrome b6/f complex. Tennis balls, covered with aluminum foil, were used as electrons, and plain green balls were used for protons. A flashlight (which we call torch light) was used as sunlight. All the characters wore placards with names of the molecules written on them in large letters with thick permanent markers.

The drama began by the plant (SR[3]; see Footnote 1 for names of the students) speaking:

"I am a plant, and this is my story of how I make use of solar energy to photosynthesize, to make food, to give you oxygen, and to grow. Photosynthesis takes place by simultaneous excitation, by photons, of chlorophyll (Chl) molecules in antenna complexes, which then transfers the energy to special reaction center molecules. As soon as light (or excitation energy) of suitable wavelength reaches say P680 in Photosystem II (PSII), an electron in it jumps to an excited energy level. Once excited, P680* passes this electron to pheophytin, which is like a Chl molecule, without the manganese in it. This electron is then carried further, downhill, to a bound plastoquinone Q_A, which is located in the PSII complex, which then passes it on to another bound plastoquinone Q_B, converting it to semiquinone (Q_B^-); after this, it accepts a proton from a nearby amino acid. Q_B^- then takes up another electron and accepts another proton, this time from a bicarbonate ion. The

[1] **Cast of Characters**: Plant/Narrator: Shirshanya Roy (SR); the Sun: (Professor) B.C. Tirpathy (BCT); Water: Hydrogen 1—Shwet Shilpi (SS); Hydrogen 2- Neelam Bhadana (NB); Oxygen- Shafaque Zahra (SZ); Tyrosine: Payal Paul (PP); P680: Mansi Gautam (MG); Pheophytin: Priya Jaiswal (PJ); Plastoquinone Q_A: Bidisha Das (BD); Plastoquinone: Q_B/Semiquinone: Q_B^-/Plastoquinol (plastodihydroquinol): Q_BH_2, or PQH_2: Chirchomri Khayi (CK) and Bapi Thokchom (BT); Bicarbonate ion: (Professor) Govindjee (GOV); Rieske iron-sulfur cluster of Cytochrome (Cyt) b6/f complex—Rashmi Baraik (RB); Cyt f/Cyt b6 complex itself—Pratibha Singh (PS); Plastocyanin (PC): Misha Bansal (MB); P700: Annu Kala (AK); A_0: Hima Mahour (HM); Phylloquinone (A1): Himanshi Yaduvanshi (HY); Fx: Sayed Hadi (SH); F_A/F_B: Avipsa Bose (AB); Ferredoxin (Fd): Sagarika Jaiswal (SJ); Ferredoxin-NADP oxidoreductase (FNR): Velentina Brahma (VB); $NADP^+$: Mansi Srivastava (MS); Protons: Ritu Singh (RS), and Kamal Ruhil (KR); Hydrogenase: Jyotsna (JY); Hydrogen: Ritu Singh (RS), and Kamal Ruhil (KR); and the herbicide DCMU: Shefali Bajpai (SB).

Footnote 1 continued

[2] **Components (in order of appearance; see Footnote 1 for names of the actors)**: P680; the Sun; pheophytin; Q_A; Q_B and then Q_B^-; Q_BH_2 (=PQH_2); bicarbonate; Rieske Iron Sulfur cluster; Cytb6f; plastocyanin; P700; A_0; A1; Fx; F_A/F_B; ferredoxin; FNR; $NADP^+$; proton 1 and hydrogen; proton 2 and hydrogen; DCMU; the narrator, representing the plant, was Shirshanya Roy.

[3] We have given the initials of the students next to molecules they had become in this Z-scheme drama (full names are given in Footnote 1).

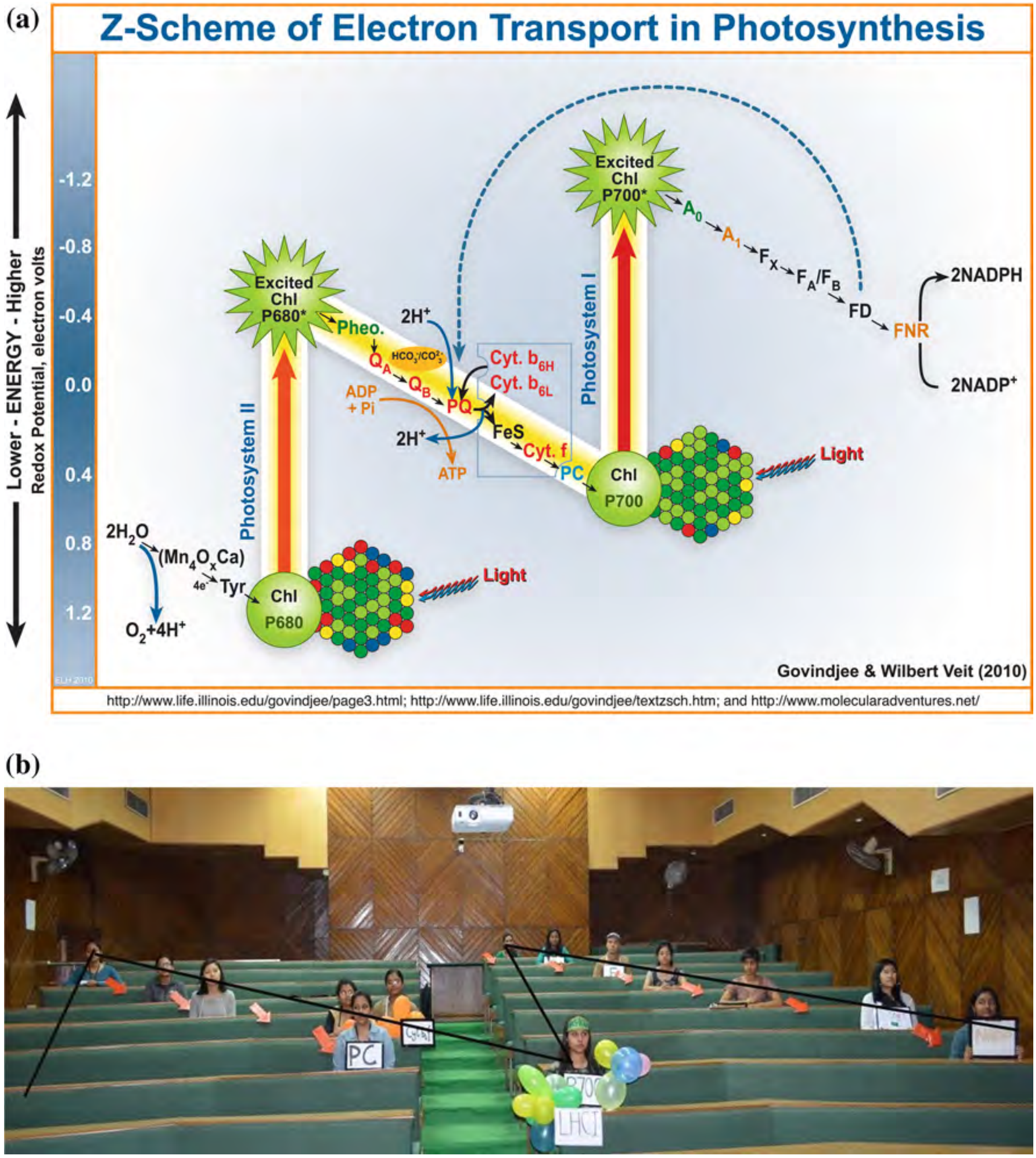

Fig. 1 **a** (*top*) A Z-scheme diagram (see discussion in the text; and the legend in Mohapatra and Singh 2015) *Source*: http://www.life.illinois.edu/govindjee; **b** (*bottom*) The students representing different molecules sit arranged according to the Z-scheme in the auditorium of the School of Life Sciences of JNU (Jawaharlal Nehru University); the water side is not shown in this photograph

resulting carbonate, in turn, accepts another proton from the stroma side (via nearby amino acids) to continue another round of this cycle. Now the reduced plastoquinone, plastodihydoquinone (called plastoquinol, PQH_2) diffuses through the thylakoid membrane towards cytochrome (Cyt) b_6/f complex and delivers electrons to the Fe-S complex, the Reiske protein, and to the Cyt b_6 cluster, releasing the protons on the lumen side. PQH_2 gets oxidized and PQ travels back to its initial position. Plastocyanin (PC) receives an electron from the reduced Rieske center, and, being mobile, delivers it to the chlorophyll in reaction center I, P700, which, after receiving excitation energy, had already delivered its electrons to another molecule of chlorophyll, Ao in PSI; thus, it being oxidized ($P700^+$), it was able to accept an electron from reduced PC. The electrons on the PSI acceptor side travel downhill till they reach $NADP^+$. The intermediate sequence of electron carriers, in PSI, includes: A1, a phylloquinone or Vitamin K; Fx, F_A/F_B, which are bound iron sulfur proteins; and ferredoxin, a somewhat mobile Fe-S protein. Next is the enzyme ferredoxin-NADP$^+$ reductase (FNR), which catalyzes the generation of NADPH.

Now, let us see how this works!

The drama begins….

(At this point Govindjee's phone rings. He says it is from Dr. Robert Emerson! It seems–they have a conversation where Dr. Emerson expresses his wish to visit and see the drama. Govindjee exits the auditorium, and re-enters the room from the back door of the auditorium, now as Emerson (Fig. 2) *himself donning the maroon colored tie and an apron that had once belonged to Dr. Emerson)*

Dr. Emerson's soliloquy
The Sun flashes light towards the Light Harvesting Complex II and the Reaction Center II
P680 [MG]: My name is P680, I am the reaction center of Photosystem ll.
Thank you, dear Sun, I have been waiting for you (Fig. 3).
(Flashes of light)
Oooo..this is so exciting,
Let me share this with Pheophytin.

(The P680 runs up the stairs–,now being P680, delivers an electron to pheophytin– comes back down to collect another electron (from the water side) and to deliver it again to pheophytin later)*

Pheophytin (PJ): Then there's me, the Pheophytin,
Now let the Z-scheme begin.
I'm now a reductant, green and strong,
This electron I'll pass along!

Q_A (BD): I am a Q_A,
Watch it, as an electron comes my way!
Now I'll pass the electron to Q_B.
Go, little electron, be free!

Fig. 2 Govindjee wearing Dr. Robert Emerson's apron and a maroon tie enacting the legendary Emerson and motivating the students

Fig. 3 Excitation of a pair of special reaction center chlorophyll *a* molecules, labeled as P680, after receiving excitons from antenna molecules, which, in turn, had absorbed photons from the sunlight (played by Prof. B. C Tripathy, not seen in the picture)

Q_B (CK): I'm also a quinone, Q_B is my name.
I carry two electrons, that's my game.
What's this? Why just one?
Should I just remain a semiquinone?

(A proton is delivered to "her" by an amino acid. Another electron is delivered next)

Oh here's the next one, about time too (Fig. 4).
But, I'm waiting for a proton from my dear friend bicarbonate (Fig. 5).
(Bicarbonate delivers a proton)
Hey, b6f, over to you!

Cyt b6f complex (PS/RB): We are gonna stay where we are,
But PSI is not very far!
Oh, Mr. Reiske, this electron,
Please, pass it on!

(A flash of light towards P700. The P700 runs up the stairs to deliver an electron, being P700, to Ao)*

Plastocyanin (MB): I'm Plastocyanin, a mobile little chap!
Here you go, P700, I'll bridge the gap (Fig. 6)!
(A second flash of light towards P700 after which it takes an electron from Plastocyanin)
P700 (AK): Hey, I see some light,
Now I'm running up the flight.
You are Ao, am I right?

Ao (HM): Yes, I am the chlorophyll next in queue
I'll pass it on to this Quinone,
Maybe, she'll know what to do.
A1 (HY): Thank you, Ao, and don't be confused.
I'll pass it on to Fx, who will now get reduced.

Fx (SH): I am an iron sulfur protein,

Fig. 4 The bound (reduced) plastoquinone Q_A^-, located in the PSII complex, passing an electron to another bound plastoquinone Q_B, converting it to semiquinone (Q_B^-)

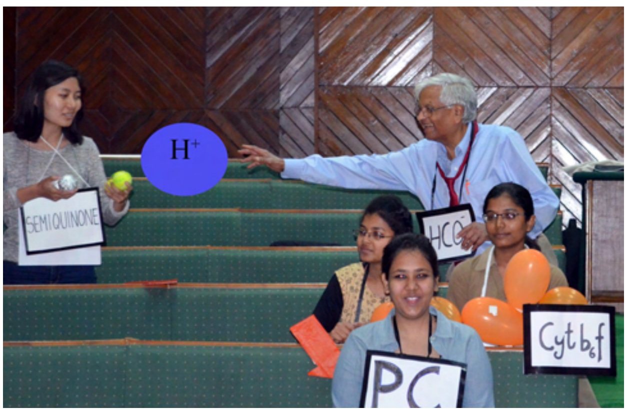

Fig. 5 Protonation at the Q_B site by the bicarbonate (HCO_3^-) ion; Govindjee plays the role of HCO_3^- giving a proton to Q_B^- "neutralizing" it, demonstrating the bicarbonate effect in the Z-Scheme

Fig. 6 The mobile plastocyanin (PC) receives an electron from the reduced Rieske iron center and passes it to the chlorophyll in the reaction center I (of PSI), P700, when it is in the oxidized state ($P700^+$) after it had been excited by "excitons" (from antenna molecules) or by photons: P700 + photon = P700* → $P700^+$, with the electron going on to reduce Ao to Ao^-

I'm brown, and not green.
Now I have to decide this electron's fate.
Else, it'll keep me in reduced state,

Hey F_A, over to you, mate!

F_A/F_B (AB):I am F_A and F_B,
I'll pass the electron to Fd (Fig. 7a).

Fd (SJ): Oo! I too contain iron-sulfur cluster,
These electrons I must muster.
Now I'm gonna pass this to you, dear reductase,
Now please, cut to the chase!

FNR (VB): I am FNR, the magic enzyme,
I will give you two electrons and bring you two together.
Abra cadabra, boom (Fig. 7b, c)!

$NADP^+$ (MS): Thank you, FNR. Now I have two electrons,
Come on, protons, now we can get along (Fig. 7d)!
(*Two protons happily come towards* $NADP^+$)

What really happens at the two ends of the Z-scheme?

The reducing equivalent, NADPH, so generated, by Photosystem I, is released into the stroma of chloroplasts. It then participates in the Calvin-Benson-Bassham cycle towards carbon assimilation for the generation of sugars.

But what about P680, in Photosystem II, which had lost its electrons, now $P680^+$? The missing electron in $P680^+$ is restored eventually by water molecules through an amino acid, tyrosine (Y_z; Y161; PP), of the oxygen evolving complex. This then is part of the oxidation of water to molecular oxygen. [We recommend a review by Barber (2016) for a detailed understanding of how plants, algae and cyanobacteria make oxygen (also see Shevela et al. 2013, for all the basic reactions, discussed in this educational report).]

H_2O (SZ): Our neighbors are sun-bathing.
Our life is sooo boring,
So let us go exploring!

Fig. 7 Ferredoxin accepts an electron from F_A/F_B, bound iron-sulfur proteins (**a**) and transfers it to ferredoxin-NADP$^+$ reductase (FNR) (**b**) that catalyzes the generation of NADPH using two protons (**c**, **d**)

Fig. 8 Oxygen is evolved by the "splitting of water" in the oxygen-evolving complex

Hydrogen 1 (SS): This oxygen is too lazy,
Making us crazy.

Hydrogen 2 (NB): So let us ask manganese,
To give us some ease,

And make this O_2 release (Fig. 8)!

(The bonds break and oxygen molecule (SZ) moves away from the hydrogen, which are now protons. Oxygen is evolved. The electron is passed on to the tyrosine molecule of the oxygen-evolving complex)

Tyrosine (PP): These neighbors do not value their electrons
So, I will pass them on.
There you go, P680, have fun (Fig. 9)!

P680$^+$ (MG): I was electron deficient.
Now this will be sufficient!

This was followed by Govindjee's monolog as a bicarbonate ion and about the function of ATP synthase—that was not covered in the drama!

The entire class in unison: I scream, you scream; We all scream for the Z- scheme!

''Not so fast, guys!'' *DCMU emerges from behind the benches. All exclaim!!*

DCMU (SB): I am a herbicide, the dreaded DCMU (Fig. 10),
And I have come here to destroy you!
So move aside, Q_B,
Instead of you, now it's me!
There, now I have taken your spot.
And the Z-scheme, as you all know,
Is now blocked!

(The characters, cytb$_6$/f complex onwards, start falling one after the other after DCMU displaces Q_B)

DCMU, a herbicide, which stalls or inhibits photosynthesis, disrupts the process of electron transport from PS II to PS I by replacing Q_B, thus, disallowing the electron transfer to the subsequent carriers. As a result, the ability of the plant to transform light energy into chemical energy is diminished. But on the greener side (pun intended), this

Fig. 9 An amino acid Yz (Y161) is a special tyrosine molecule transferring electrons to the oxidized reaction center chlorophyll a molecule ($P680^{+}$) of PSII

herbicide is often used to eliminate the invasive weeds in the fields.

Well, well, the story does not end here, says the "plant" (SR): We green things capture light not only to generate NADPH and ATP to fix carbon dioxide, but can also produce a fuel that is cleaner and has been found to be quite efficient: Hydrogen gas. This process is similar to the Z-scheme you just saw, but with a new magician enzyme, the hydrogenase.

Let us have a look at the scheme once again, but this time, with hydrogenase in place: Possibility of Hydrogen evolution instead of sugars

The same dialogs follow as above till F_A.

Ferredoxin (SJ): Participating in more than one cycle of electron flow,
I am Ferredoxin, as you all know.
Take these electrons, hydrogenase enzyme,

Fig. 11 Under special conditions, photosynthetic systems can be made to evolve hydrogen molecules, using the hydrogenase enzyme (**a**), instead of the FNR, as in the normal Z-scheme, and the protons nearby (**b**)

And, hurry up! We are running out of time (Fig. 11a)!

(Hydrogenase passes the electrons and hydrogen is evolved)

Hydrogen molecule (RS and KR): We are hydrogen (Fig. 11b), we are so cool,

Fig. 10 DCMU, a herbicide, inhibits photosynthesis by displacing Q_B, and, thus, preventing the electron flow from Q_A^- to the plastoquinone

Fig. 12 The entire cast of the Z-scheme drama

Fig. 13 A photograph of the authors, and part of the team behind the Z-scheme drama. *Top left* Sagarika Jaiswal (who acted as "ferredoxin"); *top right* Misha Bansal (who played the role of plastocyanin); *bottom left* Shirshanya Roy (the narrator or the plant); *bottom right* (*left* to *right*) Adyasha Bharti (who wrote the text of the narrative, and took the photographs), Govindjee (who checked the proofs and acted as bicarbonate), and Barnali Padhi (who wrote the text of the narrative, organized the manuscript, and is the corresponding author of this paper)

We can be used as a clean fuel!
The pollution rate is up, and it's alarming,
But together, we can fight this global warming.

We are told that hydrogen fuel is a zero- emission fuel when burned with oxygen. It is being explored as a fuel for passenger vehicles. It can also be used in fuel cells to power electric motors or burned in internal combustion engines. It is an environmentally friendly fuel that has the potential to dramatically reduce our dependence on imported oil. But significant challenges must be overcome before it can be widely used (Source: fueleconomy.gov; Hydrogen; www.fueleconomy.gov). See Zannoni and De Philippis (2014) for a discussion of hydrogen production from microbiological sources, and compare it with normal physiology and biochemistry of plants (Leegood et al. 2000).

Concluding remarks

This was our story. We wish to point-out that the motivation of teaching Z-scheme of photosynthesis in the way, as explained by Govindjee, with which we agree, was that it involved group learning; it engaged many more senses than simply listening to a lecture; it certainly encouraged us to think about modeling processes that we could only see in our "mind's eye" and then we were able to construct a functioning model, with the extra stimulation of acting the parts ourselves. After participating in the drama, we felt a quantum jump in our understanding of the concepts and details of the process.

We do want to point out that this drama can be modified in two ways: (1) It can be made more realistic by simultaneously exciting both photosystems at the same time, which can then be followed by the reactions on the water oxidation; intersystem electron transport between pheophytin and plastocyanin; and reduction of $NADP^+$ to NADPH. (2) It can be made simpler for less advanced students by leaving out: (a) several intermediates; (b) role of bicarbonate; and (c) the alternate production of hydrogen.

We end this narrative by showing photographs of the entire group, gathered after the show (Fig. 12), and of the authors, some with Govindjee (Fig. 13). Additional photographs are shown in the Supplementary Material.

Acknowledgments We are highly obliged to GIAN (Global Initiative of Academic Networks) of Government of India for supporting the visit of Govindjee (Professor Emeritus, University of Illinois, Urbana–Champaign) to teach us a course on Photosynthesis during February, 2016, together with Prof. B.C. Tripathy of JNU. A course description is available at http://www.life.illinois.edu/govindjee/teachingof.html. We thank the entire class of M.Sc. for their participation in this educational drama done in a classroom. We thank Govindjee for his ingenious idea of representation of the Z-scheme phenomenon, and for correcting the conceptual errors, as well as for playing the role of bicarbonate, but most importantly for acting as Robert Emerson during the drama. We are grateful to Prof. B.C. Tripathy for helping us out with the drama, making us rehearse over and over again, and for playing the part of Sun so well. We are extremely obliged to Prof. Thomas D. Sharkey, editor of our manuscript, for making several crucial suggestions that have improved this REPORT. Three of us (Sagarika Jaiswal, Misha Bansal, and Shirshanya Roy) wrote the text of the drama; and two of us (Adyasha Bharati, and Barnali Padhi) wrote the text of the narrative, and provided additional help and ideas, and stayed back late during rehearsals. We are especially thankful to Ritu Singh and Shefali Bajpai for agreeing to act as hydrogen and DCMU, respectively; we are also pleased that Kamal Ruhil accepted, at the last minute, to act as a proton! Our heartfelt thanks go to Anand Gupta and Ehteshamul Haq for patiently videotaping the entire event, and to Adyasha Bharati who took all the photographs of the Z-scheme drama. Lastly, we thank Rajni Govindjee for celebrating our success with a luncheon for the entire MSc class.

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Supplementary Material

For the **Educational News Report** on **“Electron flow from water to $NADP^+$ with students acting as molecules in the chain: A Z-Scheme drama in a classroom”**

by

Sagarika Jaiswal, Misha Bansal, Shirshanya Roy, Adyasha Bharati, and Barnali Padhi

Barnali Padhi and Adyasha Bharti added the following figures and text for the above News Report

(A) Additional photographs of several participants, either from the Tripathy Lab (Figures S1a and S1b), or from the Z-Scheme drama (Figure S2). **(B)** Some comments by students from the photosynthesis course given in February, 2016, by Govindjee and B.C. Tripathy. (**C)** Finally, we have added a photograph of a cake with Z-scheme, presented to Govindjee by James Dalling, Head of Plant Biology, at the University of Illinois at Urbana-Champaign (UIUC),USA, recognizing Govindjee’s 60 years at UIUC in September, 2016 **(**Figure S3a ad S3b**).**

A. Photographs of Govindjee and Rajni Govindjee with the Tripathy lab; for information on Govindjee, see Eaton Rye (2013), and for information on Rajni Govindjee, see Ebrey (2015)

Fig. S1 (**a**) Left to right: Kamal Ruhil; Adyasha Bharati; Garima Chauhan;, Sampurna Garai; Govindjee; Barnali Padhi (see Demmig-Adams et al. 2014); and Deepika Kandoi

Fig. S1 (b) Left to right: Barnali Padhi; Deepika Kandoi ; Govindjee; Rajni Govindjee; and Baishnab Charan Tripathy

Fig. S2 Govindjee with some of the participants in the Z-scheme drama **(a**) Annu Kala (P700); (**b**) Left to right: Shafaque Zahra (Oxygen), Govindjee (Bicarbonate); Jyotsna (Hydrogenase), and Sagarika Jaiswal (Ferredoxin).(**c**) Neelam Bhadana (protons);(**d**) Mansi Srivastava ($NADP^+$); (**e**) Priya Jaiswal (Pheophytin) and Noor Sadeq (FNR) ; and (**f)** Deepika Kandoi

B. Comments on Govindjee's teaching in 2016

[1] "Interesting lectures. I tried to be on time for the lectures because of [Govindjee's] GIAN (Global Initiative of Academic Networks) lectures. Thank you."—

[2] Comments from another student:

- Interesting stories about some of the amazing scientists who went to become legends in the field of photosynthesis
- Informative video clips
- Catchy songs and videos on photosynthesizing machinery
- The concept of the Z-scheme 'drama'
- So much to learn from an interesting person, Govindjee,
- Thank you GIAN!—"

[3] " The lectures were good, but I personally found some of the content difficult to understand—it could have been given in a simpler way"

[4] "Best Professor Ever, Govindjee!"

[5] "Dear Govindjee, You have been an inspiration to me—the passion and dedication you have for your area of research, your stories and your journey. Thank you for your time, for sharing your knowledge with us. The science community is lucky to have you. I wish you good health and luck in your future endeavors. Until we meet again, Love and regards, .."

[6] "Dear Govindjee: I am really lucky to have met and learned from a professor like you. Your enthusiasm is inspiring…. Thank you for introducing me to the world of endless inquisitiveness. I would love to stay in touch, and I hope that one day, I am able to inspire young minds like you do. Yours Sincerely, .."

[7] "The classes [were] so helpful, and so fun, and for me, I enjoyed so much .. in short -----Sir.. You are awesome." – ending with 2 hearts.—….

[8] “I never had “felt” plants, but after attending your lectures and watching the videos you showed in the class, I actually “felt” them! We remember scientist’s names just for the sake of exams, but after listening to your life stories, I personally believe that we should remember them for the sake of what they did, and should appreciate their contributions towards “Science”. Your ever-increasing enthusiasm is our inspiration! And Yes! I remember the Z-scheme by heart. ..ending with a smiley face and “Thank you Govindjee. “Keep inspiring and guiding us!” …

[9] “First of all, I would like to thank you, Prof. Govindjee.. I really found myself in this seminar…. I learnt how to read a research paper and how to interact with each other, and how to continue doing research. Thanks.” …

[10] “I would like to thank GIAN to have provided me such a wonderful opportunity to meet an amazing person I ever saw, a strong personality “Professor Govindjee” to learn about “Photosynthesis” from him.. He encouraged me a lot to read “news letters”, journals; also, got to know about many scientists through his classes. He suggested us many books ([including those by] Taiz & Zeiger and Blankenship) which were really helpful for me. I learnt the basics of how to give “official” presentations through the comments given by Govindjee on which I will surely work. Also, I am sure that [I] will learn a lot through the Z-scheme drama! I really liked the whole concept of GIAN. Govindjee, you are ideal for me having such a polite and kind heart. Keep inspiring and guiding us! Thank you.” [here a smiley button was pasted] –….

[11] “Thanks for giving this platform to interact with each other in a scientific manner, to give us the orientation to think in scientific manner and elaborating our views over photosynthesis.}”—…

[12] “The GIAN classes were very enlightening, both with respect to “archaic” as well as “advanced” photosynthesis. The classes significantly increased my knowledge of

photosynthesis. I am very grateful to Prof. Govindjee and Prof. B.C. Tripathy for organizing GIAN in JNU."—..

[13] "It was a privilege to attend the GIAN-JNU photosynthesis lectures by Prof. Govindjee and Prof. Tripathy. Govindjee has a distinct approach to make the classes lively and interactive. When Govindjee occasionally shared the historical anecdotes of his associates with his fellow and contemporary researchers, it threw light on the way photosynthesis related research blossomed over the decades. Tripathy Sir's lecture helped to gain a better understanding of the concepts of carbon fixation. These lectures enhanced my interest and understanding of the prokaryotic and eukaryotic photosynthetic mechanisms."

[14] " I have learnt many things from this short duration GIAN course. I really appreciate Prof. Govindjee for his good memory of recalling the names of every student. Besides a good scientist, he is a good storyteller also. I an grateful to Prof. B.C. Tripathy for teaching me basics of photosynthesis that really cleared my concepts" Anonymous

[15] " It was an honor to attend Prof. Govindjee's & Prof. Tripathy's classes. I learnt a lot about photosynthesis, probably the life-sustaining process on earth, I .. also got a glimpse of how research was conducted when technology was not as developed as it is now. One thing will not change and that is innovative ideas for science. Looking forward to your Next Visit."

[16] " Dear Govindjee, The first time I met you I was totally smitten by your energy and creative ideas. Your youthfulness as an octogenarian is inspiring and motivating for all of us. You clearly show us an example how one can take on age gracefully and increase one's and also others interest in life, We are blessed to have you among us and we truly wish that you keep inspiring us and our relationship grows over the years. It is said "the mediocre teacher tells, the good teacher explains, but a great teacher inspires and that is what you do to all of us. You and Rajniji are a great motivating factor for all of us. Once again thank you for sharing your life experiences

with us, and inspiring us with past and current advances in photosynthesis. Also, thank you Govindjee and Rajniji for your love and care. Thanks.. Lots of love."—

[17] I am so grateful to GIAN which gave me this opportunity to be in a class with such wonderful teachers. Govindjee, [I am] deeply touched and inspired by your humility. Your energy is an inspiration for me, and a motivation to seek & transfer knowledge for all the years ahead of me. It was so much fun to be sharing the history of photosynthesis with you. The classes with balls and balloons, the variety of teaching aids all have made such an impact on me on how to make teaching an interactive session rather than just bookish knowledge. Prof. Tripathy, I was so stoked to be your student. No lecture can better the words from an experienced man. I wish I was a graduate student again [to] listen to your lectures; they built up my concepts again.. Will be ever grateful to GIAN for the wonderful experience of having the opportunity to interact with the two pioneers of photosynthesis…Will wait for the next opportunity. Thanks and regards."

[18] " I had never thought that learning could be so much fun! Being from a non-Botany background, it was very enlightening for me to learn all about photosynthesis. The visual representation of the electron flow and organizing the Z-scheme drama has helped me understand the functions of each molecule. Now, I can say [that] I [will] always remember about the molecules and their sequence. I consider myself lucky to have the good fortune to be able to attend all the classes and learn.. The enthusiasm that you [Govindjee] have for the subject, after having worked on it for 56 years … I hope I have the same zeal when I reach your age. I am still in awe about the fact that you have personally interacted with all the legends of photosynthesis. For me they were all the greats who had written and worked on photosynthesis.. now knowing the human(e) facts about all of them from you, I appreciate them even better, Thank you very much Govindjee! I really enjoyed all the classes and all our interactions. I hope to see you again soon; looking forward to working with you again. Regards" .. [and a smiley face]

[19] "Dear Govindjee: I really enjoyed all the classes and all the interactions. I got to learn so much from you. Thank you very much for all your suggestions &

everything you did for me—helping my paper to be published. I am highly indebted to you."

[20] "Dear respected Govindjee (and Rajni Ma'm) — You have been for a long time a teacher and a student, but I have always found you as a father figure and guardian, both in professional as well as personal life. No words are sufficient to explain the love and affection I have received from you and Madam. My sincere gratitude ad wishes for your long and prosperous life. Hope to see both of you soon."

C. The Z-scheme cake

We end this Supplementary Material by showing a photograph of a unique cake —the Z-scheme cake that was presented to Govindjee in September 2016 after he completed 60 years at the University of Illinois at Urbana-Champaign (UIUC). See Figures S3 (a) and S3 (b) (Source: http://www.life.illinois.edu/govindjee/g/TeachingMaterial.html)

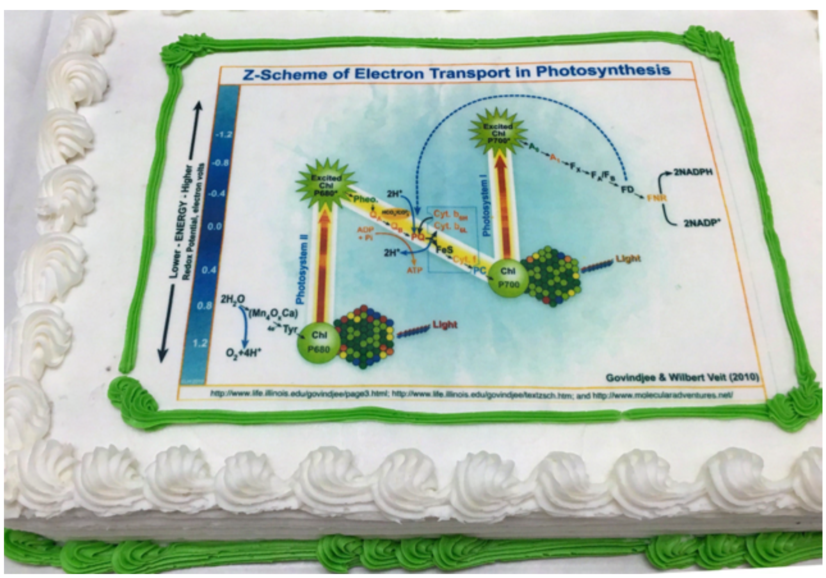

Fig. S3 (a) The Z-scheme cake; the idea of the cake was that of James Dalling, Head of Plant Biology, UIUC, and was executed by Rayme Ackerman, Office Manager, Plant Biology, UIUC; cf. it with Fig. 1b in the main text of the Educational News Report

Fig. S3 (b) Govindjee, the Z-scheme cake, and James Dalling, on September 22, 2016 ; photo by Fan Zhu.

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