Supplementary Information (SI) for RSC Sustainability.

Activity 2 Print Files

Activity 2 – A Sustainability Puzzle: Leveraging second-year inorganic principles for sustainable catalyst design.

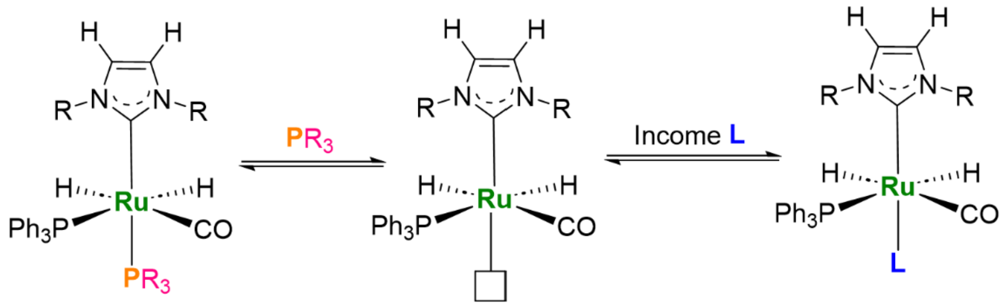
Activity 2: Breakout by Design (of Catalysts!)

Puzzle 1: Dissociative Mechanisms.

Overview of Puzzle 1

The objective of this first puzzle is to understand how different properties of a complex can influence the rates of dissociative mechanisms. The two properties being examined in this puzzle are the steric bulk of the dissociating ligand (phosphines) and the electronic properties of the trans ligand, which affect ligand lability through the trans effect (NHC ligands). To complete this puzzle, you must rank the NHC ligands and phosphine ligands, then use this information to determine the combination which may result in the fastest and slowest phosphine dissociations. Solving this will provide the combination needed to move into the next puzzle.

The general reaction can be observed below.



This puzzle is based on the metal complex above, however for simplicity, we will only be modeling the trans NHC – Metal – phosphine bonds.

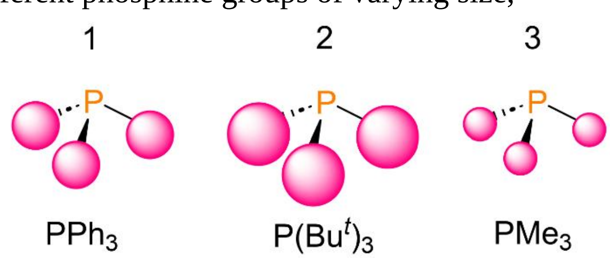
Learning objectives

By the end of this activity, you should be able to:

- Explain how steric and electronic properties affect ligand dissociation.
- Understand the trans effect and its' role in substitution mechanisms.
- Predict relative reactivity in dissociative pathways.
- Apply these ideas to rational catalyst design in green chemistry.

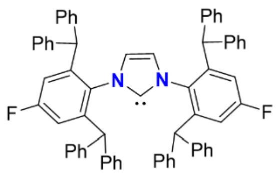
Station Procedure

1. At the station, there should be several puzzle pieces:
   a. A dowel representing the axial bond,
   b. A green bead representing the metal center,
   c. Three different phosphine groups of varying size,



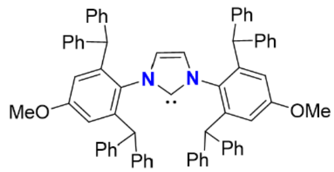
d. Three laminated NHC ligands.

1



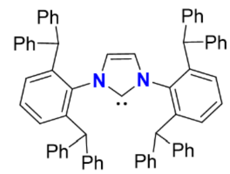
iPr*F

2



iPr*OMe

3



iPr*

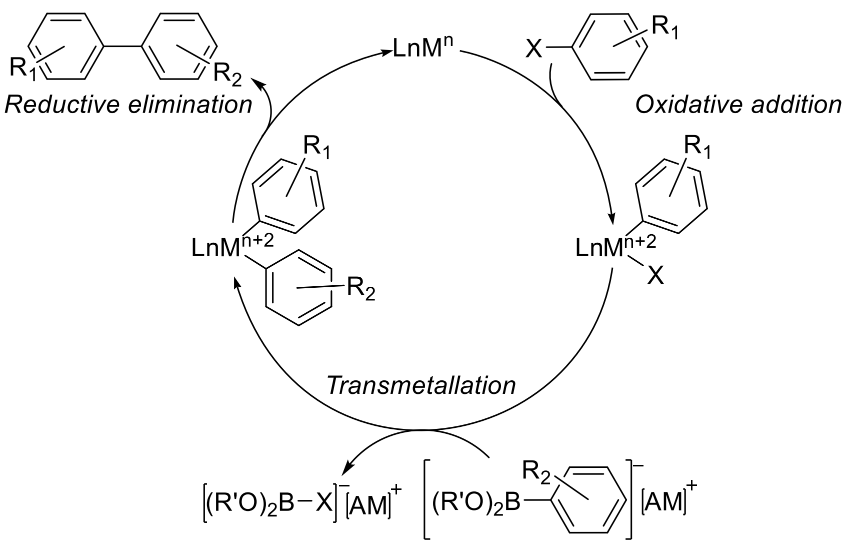
2. Review the lab notebook. It provides some valuable information on the topics listed below that may be beneficial for the puzzle.
   a. *Phosphine and NHC ligands.*
   b. *Steric and electronic effects.*
   c. *Dissociative substitution mechanisms.*
3. With this information, consider the different ligands:
   a. *Which NHC ligand would be the most donating? The least? How would this impact the bond length between it and the metal? How does this in turn impact dissociation of the phosphine?*
   b. *As the steric bulk on the phosphines increases, how does this impact the rate of dissociation?*
4. Model the substitution using the provided pieces
   a. The laminated NHC ligands are attached via velcro and can be switched out.
   b. The phosphines are represented by different 3D models that can be attached to the bottom of the dowel.
      a. Each phosphine model includes balls representing the R groups. Assume that as the size of the balls increases, so does the cone angle (i.e., steric bulk).
5. Slide the metal bead along the dowel to represent the bond length based on the NHC bond strength. Move the bead to one of the marked positions on the dowel that corresponds to the appropriate bond length
   a. *Hint: stronger bonds have shorter bond lengths.*
6. To unlock the code on Flippity, provide the ligand combination that would result in the *fastest phosphine dissociation* (corresponding phosphine number followed by the NHC number) then the combination that would result in the *slowest dissociation* (again, phosphine number followed by NHC number).

Puzzle 2: Considerations in Experimental Design for Suzuki-Miyaura Cross Coupling

Overview of Puzzle 2

The objective of this second puzzle in the escape room is to evaluate the ways in which experimental parameters are linked together, and to understand how to make the "greenest" choices. In order to complete this puzzle, you must optimize a Suzuki-Miyaura cross coupling reaction for the greenest overall experimental design. Once you have found the correct pathway, this will provide you with the information necessary to unlock the next puzzle.

The general reaction can be observed below.



Station Procedure

1) Puzzle 2 features a table of reaction conditions for Suzuki-Miyaura cross coupling. Using the erasable marker provided you must evaluate the choices in each column and circle the greenest choice on the sheet protector.
2) In order to construct a reasonable set of reaction conditions the pathway must be connected by <u>one</u> common colour (e.g. if you pick one tile with orange, purple, and red, and a second tile with blue and purple, your common colour is <u>purple</u> and every subsequent tile must contain this colour). Note, you will be able to choose your metal only after you've decided on a reaction pathway.
3) Review the lab notebook for help regarding green considerations for reaction conditions and to see relevant examples of optimized Suzuki-Miyaura cross coupling reactions with various catalyst designs.
4) With this information, consider the different choices:
    a. What type of ligand would have the lowest cost and toxicity of those listed?
    b. Which solvents are the safest to handle? Which have the lowest environmental impact and are most easily recycled?
    c. What reaction conditions are the least energy intensive? Which are the least hazardous to employ?

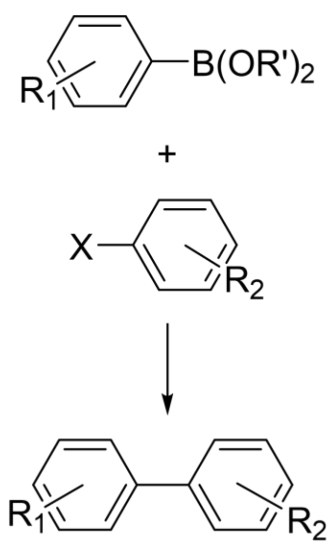
    d. Which additives pose a potential risk to safety?
    e. How might catalyst loading impact overall cost and product purification?
5) Once you've circled a choice of ligand, solvent, reaction conditions, temperature, additives, time, and catalyst loading, remove the top sheet from the sheet protector to reveal the metal colours and overall greenness of each choice (ranked by number of leaves on each tile). Circle the metal which corresponds to your chosen colour and review your pathway.
6) Edit your pathway as needed to reach the "greenest" pathway with the most possible total number of leaves. Note, exclamation points represent hazardous conditions and/or reagents, these should not be featured along your route.
7) To unlock the code on flippity, provide the metal identity and number of leaves along your pathway (eg. Co27).

Learning objectives

Through this puzzle, the following learning objectives will be emphasized:

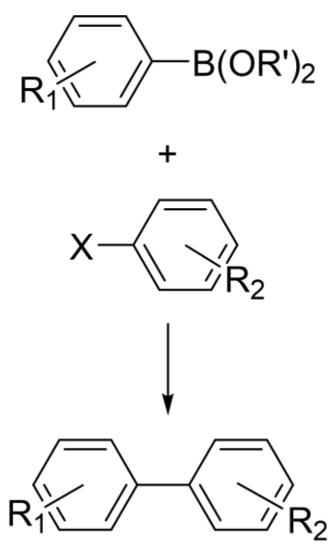
- To challenge one's perception of **green chemistry** in the context of reaction optimization.
- To expand one's understanding on the interdependence of reaction design challenges.
- To emphasize significant **barriers to sustainability** in relevant chemical reaction conditions.

Puzzle 2



Metal	Ligand	Solvent	Reaction Conditions	Temp	Additive(s)	Time	Catalyst Loading
Fe	N-based	2-MeTHF	Highly reactive with air and water	30 – 50 °C	LiR	1 – 3 hr	<0.01%
Pd	Phosphine	H_2O co-solvent	Air sensitive	70 – 100 °C	RMgX	16 – 24 hr	1 – 5%
Cu	NHC	THF	Air and water sensitive	Room temp.	KX	10 – 16 hr	0.01 – 1%
Ni	Designer ligand	Benzene	Air and water tolerant	50 – 70 °C	NaX	3 – 10 hr	> 5%

Puzzle 2



Metal	Ligand	Solvent	Reaction Conditions	Temp	Additive(s)	Time	Catalyst Loading
Fe	N-based	2-MeTHF	! Highly reactive with air and water	30 – 50 °C	! LiR	1 – 3 hr	<0.01%
Pd	Phosphine	H_2O co-solvent	Air sensitive	70 – 100 °C	RMgX	16 – 24 hr	1 – 5%
Cu	NHC	THF	Air and water sensitive	Room temp.	KX	10 – 16 hr	0.01 – 1%
Ni	Designer ligand	! Benzene	Air and water tolerant	50 – 70 °C	NaX	3 – 10 hr	> 5%

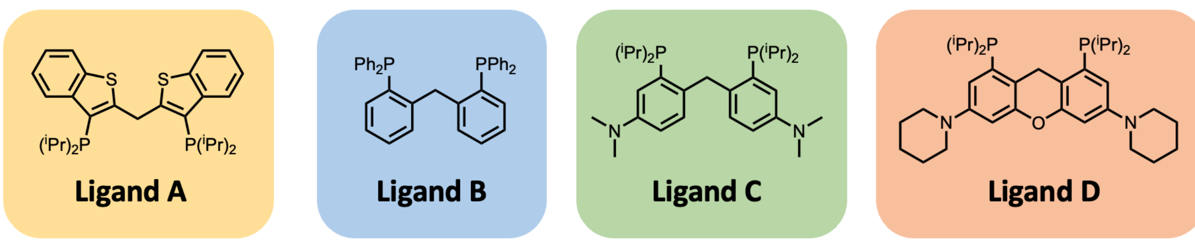
Activity 2: Breakout by Design (of Catalysts!)

Puzzle 3: Green Catalyst Design for N_2O Reduction

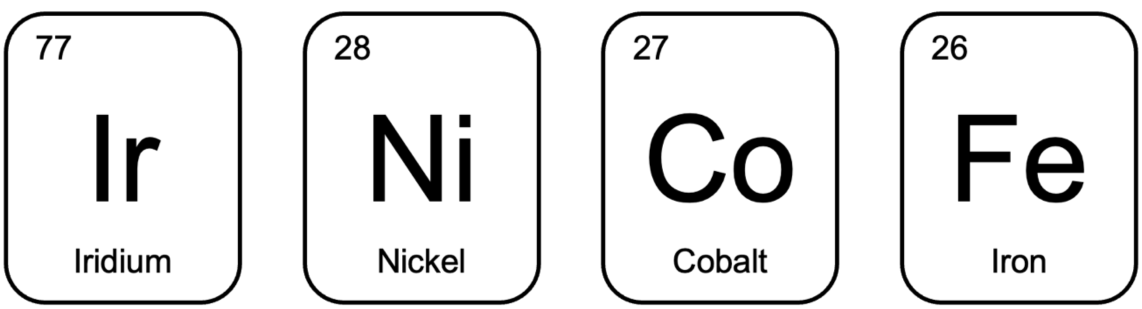
Overview of Puzzle 3

The objective of this third puzzle in the escape room is to come up with the greenest and most efficient catalyst design for nitrous oxide (N_2O) reduction. You will have the choice of four metals (iridium, nickel, cobalt, and iron) and the choice of four ligands (A, B, C, and D) and you've been left the lab notes of a previous student that highlight their synthesis and observations about these four ligands, as well as information about the metals.

In this puzzle, there are four L shaped puzzle pieces representing the four ligands the previous student had been working with:



As well as four game pieces on the lefthand side of the board representing the four metals:



Learning objectives

By the end of this puzzle, the aim is:

- To get the participants to think about balance between improved reactivity with a ligand versus greenness of the ligands, as well as with metals
- To emphasize the idea that even though a combination might be the greenest, it may not have the desired reactivity
- To illustrate that ligand and organometallic complex design is a cyclical process

Station Procedure

Puzzle #3a *(virtual lock number 3):*

1) Your first task will be to rank the ligands based on their donor strength. To do this, arrange the L shaped pieces in the puzzle board from 1 (the best donor) to 4 (the weakest donor).
2) Once you are sure of your answer, head to the virtual lock (#3) and put in the letters of the ligands in order to unlock the first part of this puzzle! (Note: put the letter of the ligand you have put in the #1 spot first, followed by the #2 spot, then so on. An example of formatting would be "ABCD" inputted into the answer field).

Puzzle #3b *(virtual lock number 4)*:

3) Once you have the outside of your puzzle completed, you will need to choose one of the ligands for your catalyst design, ensuring that it is the greenest and most effective option! To make your choice of ligand, take one of the four square pieces corresponding to your ligand of choice and place it in the middle of your puzzle (ensuring the letter is near the top of the board).
4) To make your choice of metal, choose the game piece on the lefthand side of the board corresponding to your metal of choice and move it through your now completed puzzle! You may only change directions with your piece if you hit a wall in the maze.
5) If you have chosen the correct metal, your piece should make it to one of the outcomes on the right side of the board. If you have chosen an incorrect metal, your piece will run into a wall.
6) Once you have the correct ligand in place and you are travelling through the maze with the correct metal, your piece will make it to the slot on the right indicating the correct option! To unlock virtual lock #4, input your metal choice and ligand choice in the following format: [Metal], [Ligand Letter] (ex. If the answer was zinc metal with ligand E, you would input "Zinc, E" into the answer field).

Title for the top of the puzzle board

Green Catalyst Design for N_2O Reduction

Labels for the wooden pegs

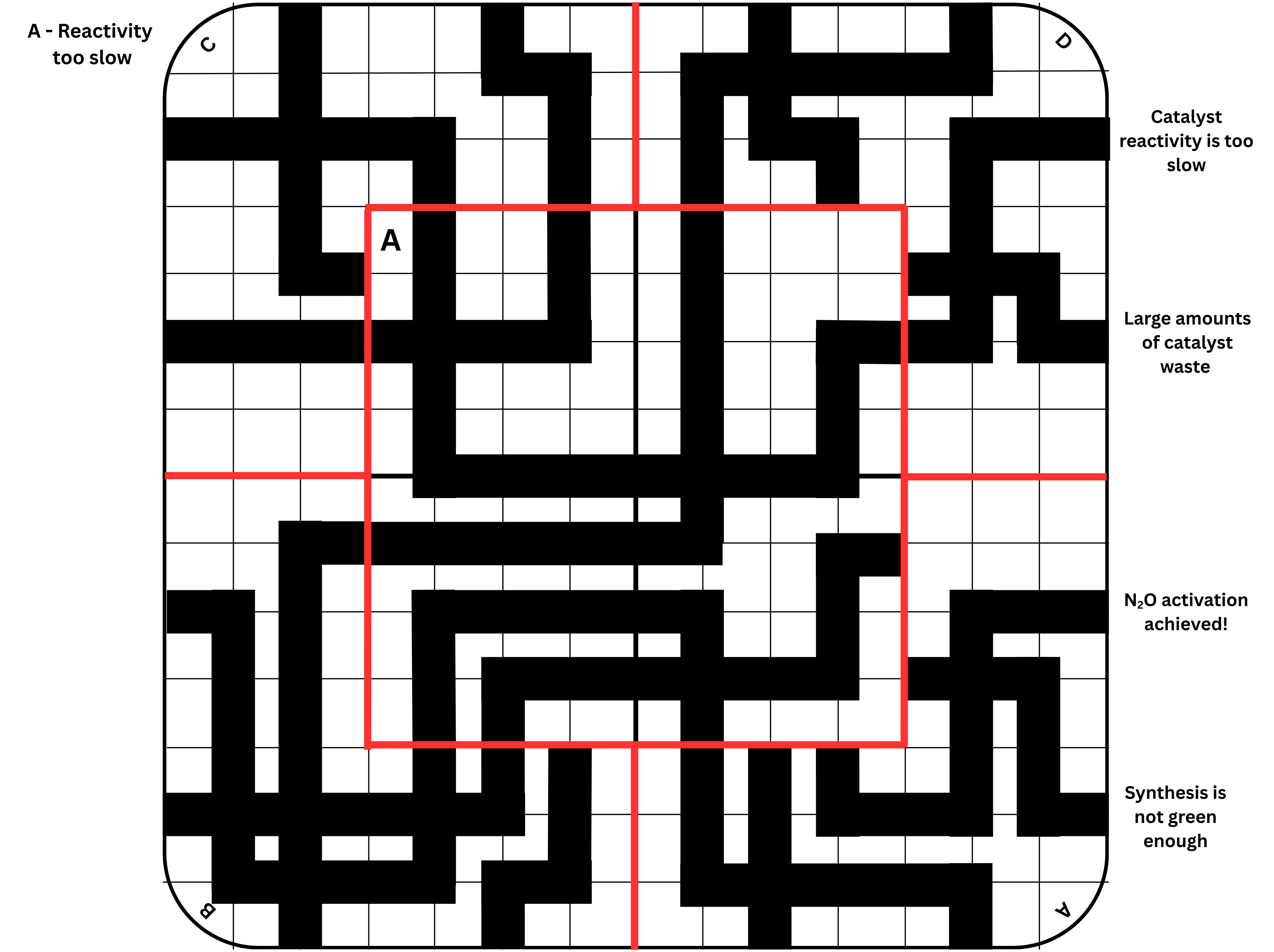
77 Ir | 28 Ni | 27 Co | 26 Fe

Labels for the puzzle board

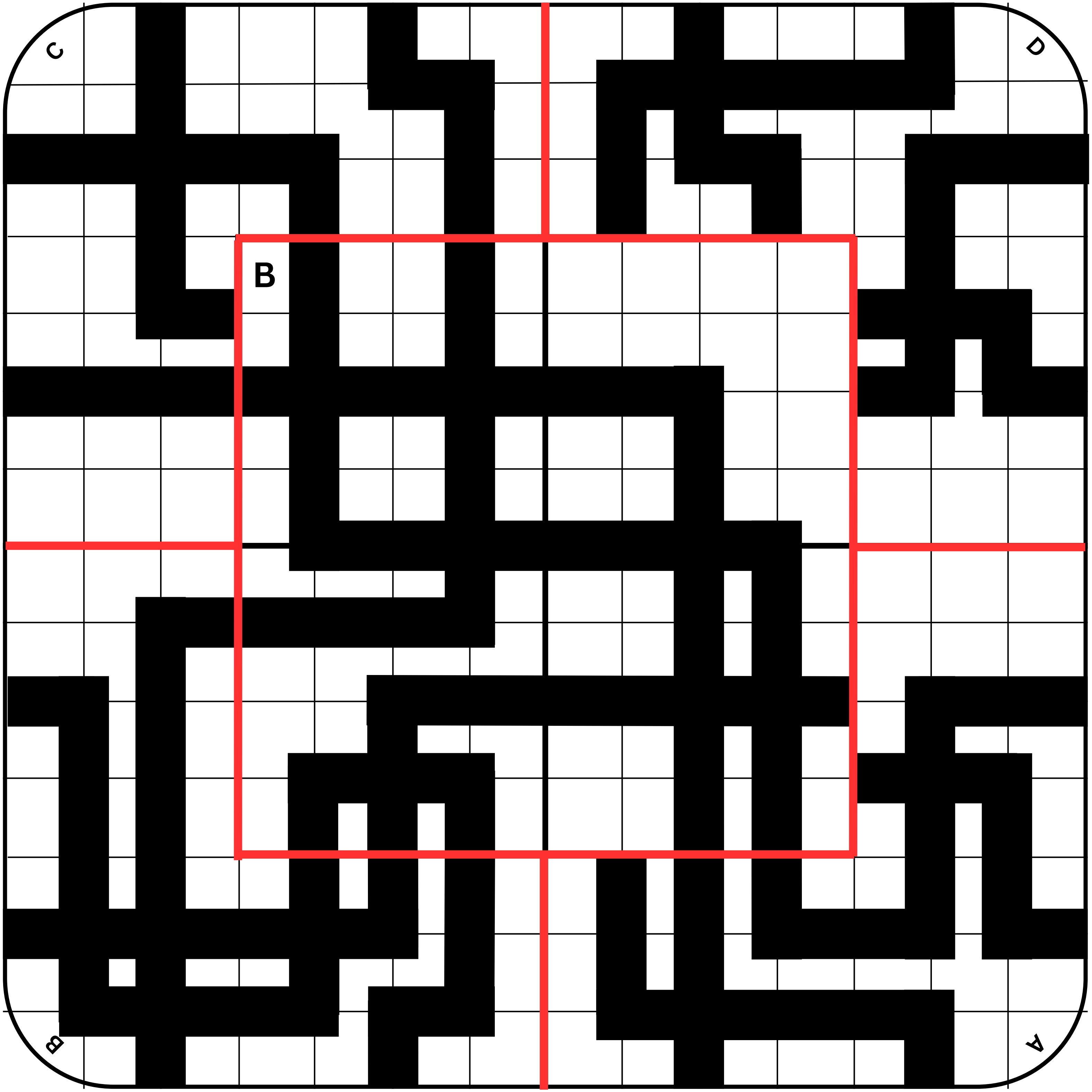
77 Ir | 28 Ni | 27 Co | 26 Fe

Outcomes for the right side of the puzzle board

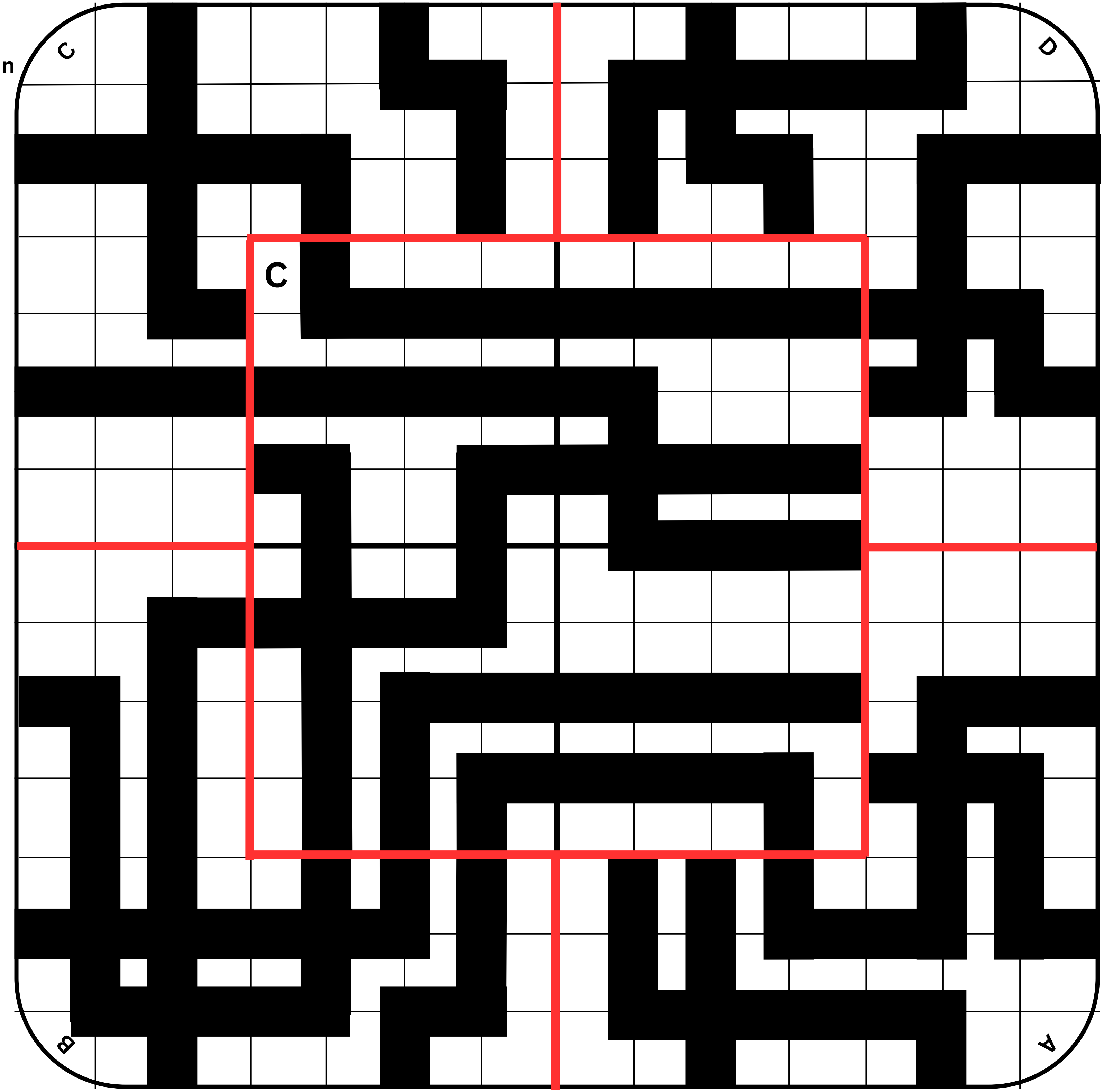
- Catalyst reactivity is too slow
- Large amounts of catalyst waste
- N_2O activation achieved!
- Synthesis is not green enough


A - Reactivity too slow
C
D
A
B
A
Catalyst reactivity is too slow
Large amounts of catalyst waste
N_2O activation achieved!
Synthesis is not green enough

B - Correct


C
D
B
B
A
Catalyst reactivity is too slow
Large amounts of catalyst waste
N_2O activation achieved!
Synthesis is not green enough

C - Catalyst decomposition

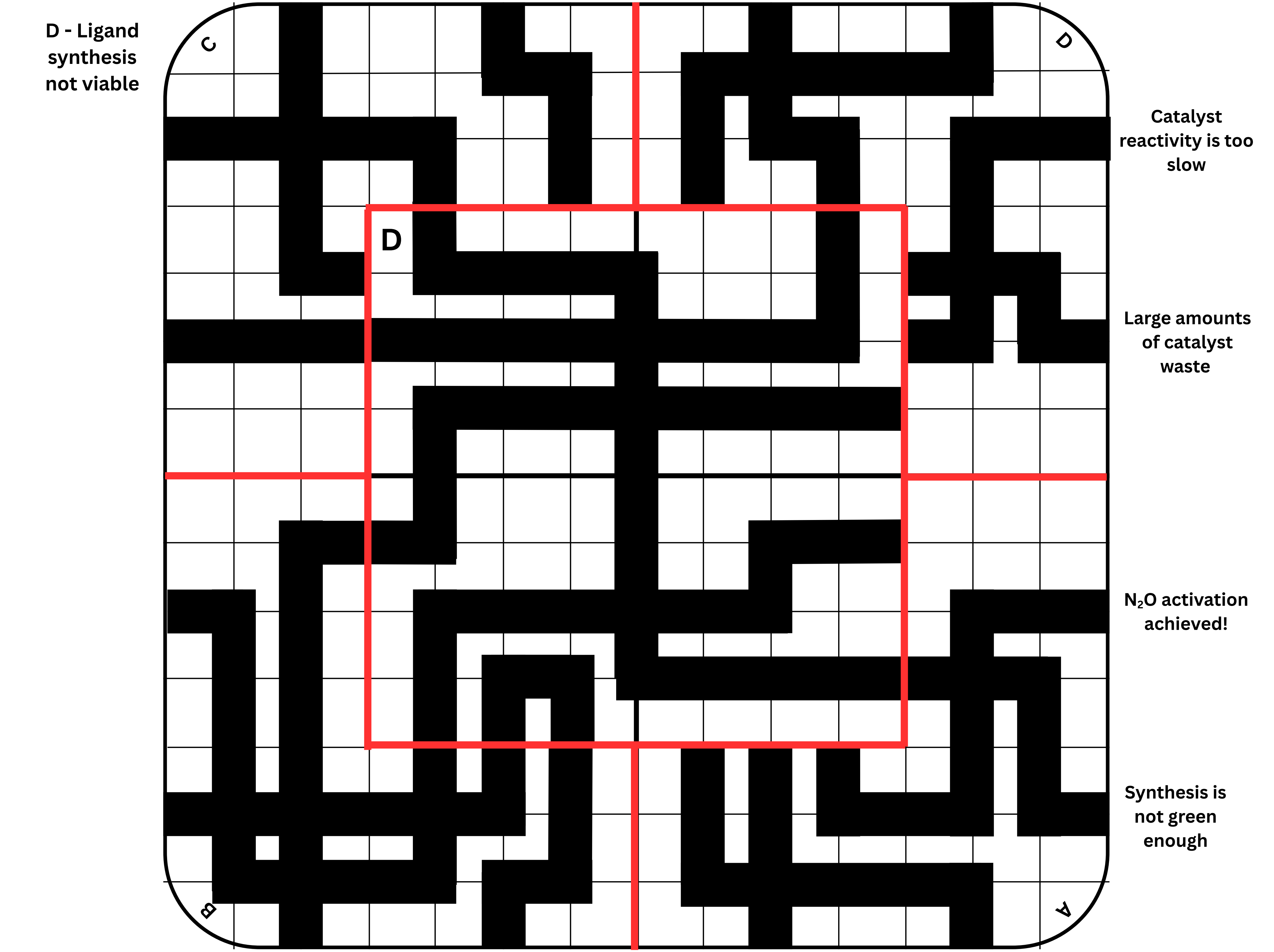


Catalyst reactivity is too slow

Large amounts of catalyst waste

N_2O activation achieved!

Synthesis is not green enough


D - Ligand synthesis not viable
C
D
Catalyst reactivity is too slow
D
Large amounts of catalyst waste
N_2O activation achieved!
Synthesis is not green enough
B
A