CHEMICAL BONDING:
WHY IS WATER DIFFERENT?

The Evidence

Jerry Bell, ACS (retired)
Bonnie Bloom, Hilliard Davidson HS, OH
For almost all familiar substances, the solid form is more dense than the liquid, as shown here for an alcohol. Water is an exception. Solid water, ice, is less dense than the liquid and floats. Why?
Why are H₂O, HF, NH₃ (and maybe HCl) so far out of line compared to the trends of the other molecules?

A. dispersion force (London force) attractions
B. dipole-dipole attractions
C. polarity
D. hydrogen bonding
Why are H_2O, HF, NH_3 (and maybe HCl) so far out of line compared to the trends of the other molecules?

A. dispersion force (London force) attractions
B. dipole-dipole attractions
C. polarity
D. hydrogen bonding

We also need to explore why the boiling points of H_2O, HF, and NH_3 go in the order shown.
What Is Hydrogen Bonding?
Recall what you know about the hydrogen bonding between two water molecules represented here by Lewis structures. Which of these structures is closest to your mental picture of the hydrogen bonding between two water molecules?

A

\[
\begin{array}{c}
\text{H} \\
\text{H} \\
\text{O} \\
\text{H} \\
\end{array}
\]

B

\[
\begin{array}{c}
\text{H} \\
\text{O} \\
\text{H} \\
\text{H} \\
\end{array}
\]

C

\[
\begin{array}{c}
\text{H} \\
\text{H} \\
\text{O} \\
\text{H} \\
\end{array}
\]

D

\[
\begin{array}{c}
\text{H} \\
\text{O} \\
\text{H} \\
\text{H} \\
\end{array}
\]
Recall what you know about the hydrogen bonding between two water molecules represented here by Lewis structures. Which of these structures is closest to your mental picture of the hydrogen bonding between two water molecules?

The strongest hydrogen bonds are formed when the hydrogen atomic core lies essentially on a straight line between the atomic core to which it is covalently bonded and the nonbonding electron pair on the other atomic core to which it is attracted.
Recall what you know about the hydrogen bonding between two water molecules represented here by Lewis structures. Which of these structures is closest to your mental picture of the hydrogen bonding between two water molecules?

The strongest hydrogen bonds are formed when the hydrogen atomic core lies essentially on a straight line between the atomic core to which it is covalently bonded and the nonbonding electron pair on the other atomic core to which it is attracted.

Three-dimensional models help to better visualize hydrogen bonds.
In the previous web seminar we introduced a balloon model of a water molecule to represent the electron waves in the molecule.
In the previous web seminar we introduced a balloon model of a water molecule to represent the electron waves in the molecule and here we introduce ball-and-stick models.
In the previous web seminar we introduced a balloon model of a water molecule to represent the electron waves in the molecule and here we introduce ball-and-stick models to help visualize hydrogen bonding.
In the previous web seminar we introduced a balloon model of a water molecule to represent the electron waves in the molecule and here we introduce ball-and-stick models to help visualize hydrogen bonding.

Requirements for hydrogen bonds of interest to us in this seminar:
• an H atom bonded to an electronegative atom, usually N, O, or F
• a non-bonding electron pair on another electronegative atom, usually N, O, or F
Questions?
Hydrogen Bonding Among Many Molecules
How many hydrogen bonds can a single water molecule form with other water molecules?

A. 1  
B. 2  
C. 3  
D. 4
How many hydrogen bonds can a single water molecule form with other water molecules?

A. 1  
B. 2  
C. 3  
D. 4
How many hydrogen bonds can a single ammonia, NH₃, molecule form with other ammonia molecules?

A. 1
B. 2
C. 3
D. 4
How many hydrogen bonds can a single ammonia, NH₃, molecule form with other ammonia molecules?

A. 1
B. 2
C. 3
D. 4
Both water and ammonia (as well as hydrogen fluoride) molecules can form hydrogen bonds with their neighbors. Energy is required to break these bonds, which explains why more energy (hence a higher temperature) is required for the liquid to gas phase change in these substances compared to what it would have been without hydrogen bonding.
Both water and ammonia (as well as hydrogen fluoride) molecules can form hydrogen bonds with their neighbors. Energy is required to break these bonds, which explains why more energy (hence a higher temperature) is required for the liquid to gas phase change in these substances compared to what it would have been without hydrogen bonding.

Since all three molecules can form four hydrogen bonds with their neighbors, the ability to form them does not explain the large differences in their boiling points, nor why ice floats on liquid water. We need to explore further.
Questions?
Even More Molecules
Consider a ring of six, H-bonded water molecules. How many Hs are available for further H bonding?
A. 0
B. 3
C. 6
D. 12
Consider a ring of six, H-bonded water molecules. How many Hs are available for further H bonding?
A. 0
B. 3
C. 6
D. 12

How many non-bonding electron pairs are available for further H bonding?
A. 0
B. 3
C. 6
D. 12
Consider a ring of six, H-bonded water molecules. How many Hs are available for further H bonding?

A. 0  
B. 3  
C. 6  
D. 12  

How many non-bonding electron pairs are available for further H bonding?

A. 0  
B. 3  
C. 6  
D. 12  

There are an equal number of Hs and non-bonding electron pairs available for further H bonding. This is a consequence of the fact that each molecule has two of each available for H bonding. Let’s see where this might lead.
Start with this 6-membered ring
Start with this 6-membered ring and bring up a second in the appropriate orientation
Start with this 6-membered ring and bring up a second in the appropriate orientation to give this extended system.
Changing our point of view, we look at the structure from the top.
Changing our point of view, we look at the structure from the top. The H bonding can be extended in three dimensions in ice crystals.
Changing our point of view, we look at the structure from the top. The H bonding can be extended in three dimensions in ice crystals, which is responsible for the shape of snowflakes.
Adding energy to the solid will cause it to melt. Let’s examine this phase change with this computer model.
Which phase has the larger amount of empty space?

A. solid

B. liquid
Which phase has the larger amount of empty space?

A. solid

B. liquid

This is why ice floats on liquid water.
Questions?
Questions?
H-Bonding Differences
Consider a ring of six, H-bonded ammonia molecules. How many non-bonding electron pairs are available for further H bonding?
A. 0
B. 3
C. 6
Consider a ring of six, H-bonded ammonia molecules. How many non-bonding electron pairs are available for further H bonding?
A. 0
B. 3
C. 6

This contrasts with the case for water molecules where we have seen that an extensive network of H-bonded molecules is possible and leads to observable properties of ice and water.
Consider a ring of six, H-bonded ammonia molecules. How many non-bonding electron pairs are available for further H bonding?

A. 0
B. 3
C. 6

This contrasts with the case for water molecules where we have seen that an extensive network of H-bonded molecules is possible and leads to observable properties of ice and water.

Let’s examine this contrast in a different way.
Consider a sample containing $N$ water molecules, where $N$ is a very large number.

How many Hs are available for H bonding?

A. $N$
B. $2N$
C. $3N$
D. $4N$
Consider a sample containing $N$ water molecules, where $N$ is a very large number.

How many Hs are available for H bonding?
A. $N$
B. $2N$
C. $3N$
D. $4N$

How many non-bonding electron pairs are available for H bonding?
A. $N$
B. $2N$
C. $3N$
D. $4N$
Consider a sample containing $N$ water molecules, where $N$ is a very large number.

How many Hs are available for H bonding?
A. $N$
B. $2N$
C. $3N$
D. $4N$

How many non-bonding electron pairs are available for H bonding?
A. $N$
B. $2N$
C. $3N$
D. $4N$

What is the maximum number of H bonds that can be formed?
A. $N$
B. $2N$
C. $3N$
D. $4N$
Consider a sample containing $N$ water molecules, where $N$ is a very large number.

How many Hs are available for H bonding?
A. $N$
B. $2N$
C. $3N$
D. $4N$

How many non-bonding electron pairs are available for H bonding?
A. $N$
B. $2N$
C. $3N$
D. $4N$

What is maximum number of H bonds that can be formed?
A. $N$
B. $2N$
C. $3N$
D. $4N$

An H bond requires an H and a non-bonding electron pair. There are $2N$ of each.
Consider the same analysis for a sample containing $N$ ammonia molecules.

How many Hs are available for H bonding?

$3N$

How many non-bonding electron pairs are available for H bonding?

$N$

What is maximum number of H bonds that can be formed?

$N$

An H bond requires an H and a non-bonding electron pair. There are only $N$ non-bonding electron pairs available, so the maximum number of H bonds is limited to $N$. 
Consider the same analysis for a sample containing $N$ ammonia molecules.

How many Hs are available for H bonding?

$3N$

How many non-bonding electron pairs are available for H bonding?

$N$

What is maximum number of H bonds that can be formed?

$N$

An H bond requires an H and a non-bonding electron pair. There are only $N$ non-bonding electron pairs available, so the maximum number of H bonds is limited to $N$.

This same sort of analysis applies to a sample of hydrogen fluoride molecules in which the maximum number of H bonds, $N$, is limited by the number of Hs available.
Since a sample of H$_2$O has the potential to form twice as many H bonds as a similar sample of NH$_3$ or HF, we can understand why it takes so much more energy (a higher temperature) for the liquid to gas phase change in water.
Since a sample of H$_2$O has the potential to form twice as many H bonds as a similar sample of NH$_3$ or HF, we can understand why it takes so much more energy (a higher temperature) for the liquid to gas phase change in water.

Our analysis suggests that the H-bonding capacity of samples of NH$_3$ and HF might be roughly the same. Since F has a higher electronegativity than N, the H bonds in HF are stronger and its boiling point higher than NH$_3$. 
Since a sample of H₂O has the potential to form twice as many H bonds as a similar sample of NH₃ or HF, we can understand why it takes so much more energy (a higher temperature) for the liquid to gas phase change in water.

Our analysis suggests that the H-bonding capacity of samples of NH₃ and HF might be roughly the same. Since F has a higher electronegativity than N, the H bonds in HF are stronger and its boiling point higher than NH₃.

H bonding, coupled with the structure of the water molecule, have provided the answers to the questions posed at the start of this web seminar. Have you further questions?
Questions?
Thank you to the sponsor of tonight's Web Seminar:

This web seminar contains information about programs, products, and services offered by third parties, as well as links to third-party websites. The presence of a listing or such information does not constitute an endorsement by NSTA of a particular company or organization, or its programs, products, or services.
Welcome to Your Personalized Learning Web Space!

Paul, you've already earned **1015 Activity Points**!

- You've recently earned: 
  - Ruby Aggregator
  - Add Personal Resources

- You're close to earning:
  - Ruby Commenter
  - Post 9 more comment/questions

**UPDATE YOUR PROFILE**  **CHECK THE LEADERBOARDS**

With these resources, you can build your professional development plan, track your activities, and assess your progress. You can start at "Explore Learning Opportunities" below or by creating a game plan with the PD Plan and Portfolio tool. You may also review an archived Web Seminar or a multimedia overview of the Learning Center.

**Explore Learning Opportunities**
- Advanced Search
- See all FREE Lesson Plans
- See all FREE Resources

By Subject  By Grade Level  By State Standards

http://learningcenter.nsta.org
National Science Teachers Association
Dr. Francis Q. Eberle, Executive Director
Zipporah Miller, Associate Executive Director
Conferences and Programs
Al Byers, Assistant Executive Director e-Learning

NSTA Web Seminars
Paul Tingler, Director
Jeff Layman, Technical Coordinator

LIVE INTERACTIVE LEARNING @ YOUR DESKTOP