Lesson 3: Nanofiltration

Teacher Materials

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Nanofiltration: Teacher Lesson Plan

Orientation

As a dynamic, evolving area of science, nanotechnology can provide an exciting learning opportunity for students, offering them the opportunity to learn about current science and technology innovations that may improve our world. The use of nanofiltration for cleaning water is one such innovation. Scientists are working to develop newer, cheaper and more effective membrane technologies to clean water. Much of the current work has focused on new designs of nanofilters, and nanofiltration systems are currently deployed in a few metropolitan areas.

Learning about nanofiltration also reinforces important fundamental chemistry concepts that are sometimes difficult for students to grasp. Students must understand differences in solution types to understand how different filtration systems work on a small scale. The topic of nanofiltration also has the potential to help students see interdisciplinary connections between biology, chemistry, and engineering.

The lessons in the Fine Filters unit focus conceptually on the role of membrane technology for filtering water. The presentation, notes, activities and readings focus on key aspects of filtration such as underlying technologies, particle filtration sizes, and applications.

- The Nanofiltration Teacher and Student Readings provide background on how nanofiltration works. The teacher reading is recommended prior to presenting the Nanofiltration PowerPoint slides and other activities.
- The Nanofiltration PowerPoint slide set provides a brief introduction to the different types of filtration and how they work, with emphasis on nanofiltration methods.
- The Which Method is Best exercise is a worksheet activity that allows students to explore some of the basic ideas of filtration, such as membranes and particle size, and prepares them for the more involved lab activity.
- The Comparing Nanofilters to Conventional Filters lab activity gives students a hands-on opportunity to better understand two types of filtration.
- The Cleaning Jarny's Water exercise allows students to explore ideas of filtration in a real-world application.
- The New Nano-Membranes Reading introduces students to current research in creating nanotechnology membranes
- The Reflecting on the Guiding Questions Worksheet asks students to connect their learning from the activities in the lesson to the driving questions of the unit.

Essential Questions (EQ)

What essential question(s) will guide this unit and focus teaching and learning?

(Numbers correspond to learning goals overview document)

2. How do we make water safe to drink?
3. How can nanotechnology help provide unique solutions to the water shortage?

Enduring Understandings (EU)

Students will understand:

(Numbers correspond to learning goals overview document)

3. Pollutants can be separated from water using a variety of filtration methods. The smaller the particle that is to be separated from a solution, the smaller the required pore size of the filter and the higher the cost of the process.
4. Innovations using nanotechnology to create a new generation of membranes for water filtration are designed to solve some critical problems in a cost-effective way that allows for widespread use.

Key Knowledge and Skills (KKS)

Students will be able to:

(Numbers correspond to learning goals overview document)

2. Describe different types of filtration in terms of the pore size of the filter, substances it can separate, and cost of use.
3. Use laboratory procedures to compare the relative effectiveness of different filtration methods on particle separation.

Nanofiltration Timeline

Day	Activity	Time	Materials
	Homework: Nanofiltration: Student Reading	*20 min*	Photocopies of Nanofiltration: Student Reading
Day 1 (50 min)	Show the Nanofiltration PowerPoint slides, using the teacher's notes to start class discussion.	30 min	Nanofiltration PowerPoint Slides & Teacher Notes Computer and projector
	Hand out the Which Method is Best? Student Worksheet and The Filtration Spectrum: Student Handout and have students work in small groups to answer the questions.	10 min	Photocopies of Which Method is Best? Student Worksheet Photocopies of The Filtration Spectrum: Student Handout
	Return to whole class discussion and have students share their ideas on which types of membrane can filter which type of particles. You may want to have different students each draw a particular membrane and related filtrated particles to help drive class discussion. This activity is a preparation exercise for the lab that will take place on day 2 of this lesson. Pre-read the lab and give students an indication of what to expect during the next class session.	10 min	Comparing Nanofilters to Conventional Filters Lab Activity: Teacher Instructions
	Homework: Read the Comparing Nanofilters to Conventional Filter Lab Activity: Student Instructions in preparation for the next class.	*25 min*	Photocopies of the Comparing Nanofilters to Conventional Filters Lab Activity: Student Instructions

Day 2 (50 min)	Have students work in pairs or small groups on the Comparing Nanofilters to Conventional Filters Lab Activity. Each student should complete their own Student Worksheet, although they may consult with other group members or the teacher.	50 min	Photocopies of the Comparing Nanofilters to Conventional Filters Lab Activity: Student Worksheet
	Homework: New Nano-Membranes: Student Reading	*15 min*	Photocopies of New Nano-Membranes: Student Reading
Day 3 (50 min)	Have students work on the Cleaning Jarny's Water activity in small groups.	25 min	Photocopies of Cleaning Jarny's Water: Student Instructions & Report
	Have students discuss the New Nano-Membranes: Student Reading in small groups.	10 min	Photocopies of the New Nano-Membranes: Student Reading
	Have students work individually or in small groups to fill out the Reflecting on the Guiding Questions: Student Worksheet.	10 min	Photocopies of Reflecting on the Guiding Questions: Student Worksheet
	Discuss the Essential Questions and the group's collective ability to answer them based on the work done in the unit and answer any remaining student questions.	5 min	

Nanofiltration: Teacher Reading

How is Water Cleaned?

Water cleansing is complex. There are many methods for making water safe to drink. In addition, new technologies are being researched and patented at a relatively rapid rate. Typically, water is cleaned through multi-step processes that balance efficacy (i.e. contaminant removal) with cost-effectiveness.

Non-Filtration Techniques

While filtration is the main technique used to clean water, there are several common methods of cleaning water that are used independently and/or in addition to filtration.

- **Distillation** processes use heat to evaporate water. The gas then condenses, leaving all impurities behind except those (some pesticides and fertilizers) with boiling points lower than water that get evaporated and then condensed along with the water. This method is expensive. It also leaves the water tasteless, and without minerals.
- **Ion exchange** methods work by passing ion-containing water through resin beads, which exchange OH^- and H^+ ions for the unwanted ions.
- **UV** methods use ultraviolet light as a germicide to kill bacteria and other microorganisms in water. These methods do not remove particulates or ions.
- **Chemical-based** methods are used to cause flocculation (the formation of small clumps of particles, making them easier to remove), precipitation or oxidation of particles.

Water Filtration

Filtration is the process of passing a fluid through a porous object or objects (for example cheesecloth or sand) in order to separate out matter in suspension [1]. Filtration is the primary process used to clean water for human use.

Some Vocabulary Clarification

Many words with similar meanings are used to describe parts of the filtration process. These words are used interchangeably in the water filtration literature. These words and their meanings are illustrated in Figure 1.

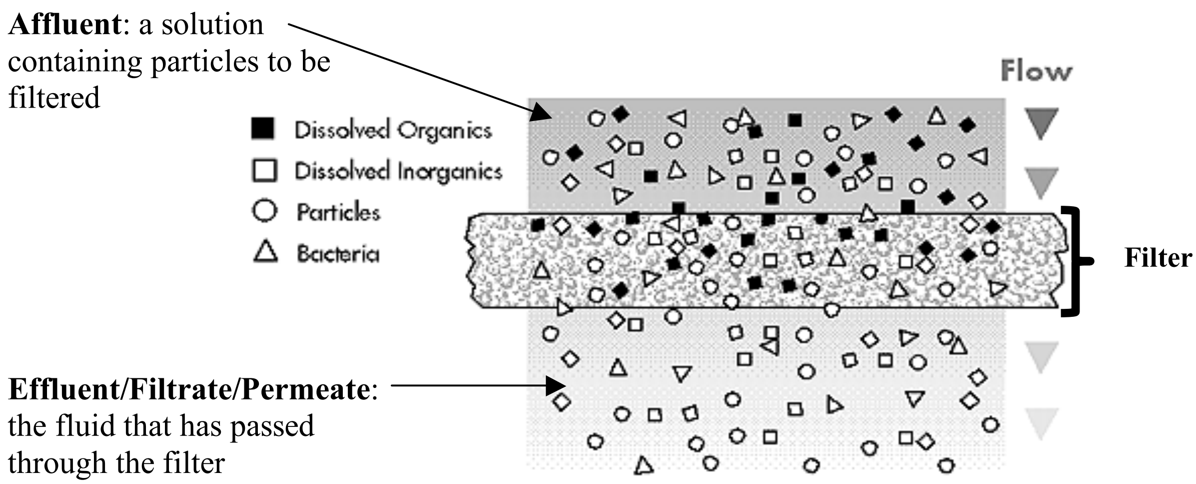


Figure 1. Particles passing through a carbon filter [2].

Kinds of Filtration

The following is a list of commonly used filtration types. All of them use membrane technologies, except for carbon filtration which uses a collection of small grains. Each of these filter types are expanded upon in Table 1, including examples of particle types they can remove and diagrams of the filters. A simplified version of Table 1 is also provided as a student handout (Types of Filtration Systems and their Traits: Student Handout).

- **Carbon filtration** traps larger organic particles on the surface of small carbon grains. Different types of filters are capable of trapping different substances.
- **Microfiltration** methods employ depth, screen or surface membranes:
    - **Depth filters** consist of matted fibers that retain particles as they pass through the filter. About 98% of the particles passing through this type of microfilter are retained, protecting finer-scale membranes farther down the chain. Depth microfilters are considered good prefilters for this reason.
    - **Surface filters** are multilayered structures that remove 99.99% of suspended solids, and are also used as prefilters.
    - **Screen filters** are microporous membranes that trap particles based on the specific pore size of the membrane.
- **Ultrafiltration** methods employ a thin, yet tough, membrane with a very small pore size.
- **Nanofiltration** methods focus on pore size, charge (repulsion), and shape characteristics of the membrane. A moderate amount of pressure is required for nanofilters to operate effectively.

- **Reverse osmosis** methods use a selectively-permeable membrane to separate water from dissolved substances. Relatively high pressure is required to make water flow against normal osmotic pressure.

Filtration Trade-offs

Generally, the smaller the filter, the more pressure is needed to push the water through it. Greater pressure means a greater cost, and so filters that remove very small particles are the most expensive to use. To be cost-effective, filtration is usually done as a multi-step process. Bigger contaminants are first removed using large-pore (and thus less expensive) filters, then filters with decreasing pore sizes are used to remove smaller and smaller particles. Using a sequence of filters also keeps the small-pore filters from getting clogged up with the large contaminants. This clogging is called "fouling." Filters must be cleaned regularly to remain usable

State of the Art?

While constantly improving, our current water purification technology is inadequate to meet the current or the projected needs of the world's population for clean drinking water. New nanofilters are being explored with much anticipation and excitement for their potential to address the global water crisis.

References

(Accessed December 2007.)

[1] http://www.m-w.com/dictionary/filter

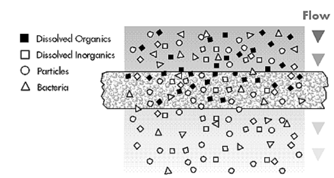
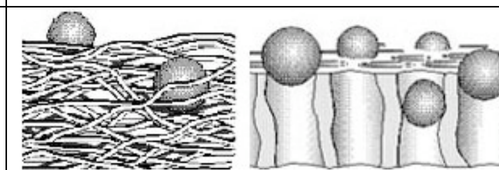
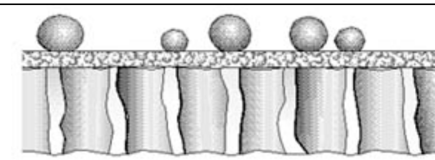
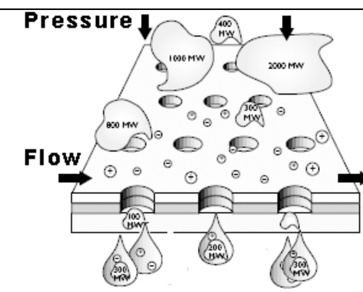
[2] Adapted from http://www.freedrinkingwater.com/water-education/quality-water-filtration-method.htm

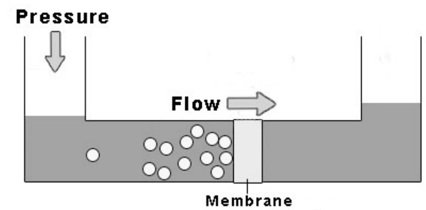
[3] Adapted from http://www.homecents.com/images/h2o-imgs/nano_f_l.gif

[4] Adapted from http://www.zenon.com/image/resources/glossary/reverse_osmosis/reverse_osmosis.jpg

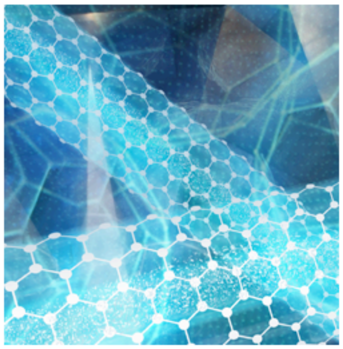
[5] http://www.nesc.wvu.edu/ndwc/

Table 1. Types of Filtration Systems and their Traits

Type of Filtration	Max Particle Size (meters)	Characterization	Example Particles	Disadvantages	Diagram
Carbon Filtration **(CF)**	Above 10^{-6}	Large organic particles are trapped on the surface of small carbon grains. Used in combination with other filtration processes.	Removes bad tastes and odors (organic matter) and chlorine Varies widely	No effect on total dissolved solids, hardness, or heavy metals.	 [2]
Microfiltration **(MF)**	10^{-5} to 10^{-7}	Removal based on relatively large pore size, retains contaminants on surface. Very low water pressure needed. Often used as a pre-filter.	Sand, silt, clays, *Giardia lamblia, Cryptospoidium*, cysts, algae and some bacteria	Removes little or no organic matter. Does not remove viruses.	 Depth Filter Surface Filter [2]
Ultrafiltration **(UF)**	10^{-7} to 10^{-8}	Removal based on smaller pore size, retains contaminants on surface. Low water pressure needed.	Suspended organic solids Partial removal of bacteria Most viruses removed	Most problems are with fouling. Cannot remove iron or manganese ions (multivalent ions).	 [2]
Nanofiltration **(NF)**	10^{-8} to 10^{-10}	Removal based on very small pore size and shape and charge characteristics of membrane. Moderate pressure needed.	Suspended solids Bacteria Viruses Some multivalent ions	Currently most are susceptible to high fouling. Cost is relatively high (currently).	 [3]

Reverse Osmosis **(RO)**	10^{-9} to 10^{-11}	High pressure process that pushes water against the concentration gradient Different membranes have different pore sizes and different characteristics.	Suspended solids Bacteria Viruses Most multivalent ions Monovalent ions	Membranes are prone to fouling. Cost is high.	 [4]

Note: Relative Pressure needed for operation: RO > NF > UF > MF **Relative Cost**: RO > NF > UF > MF [5]



Nanofiltration

Environmental scientists and engineers are creating nanomembranes to filter contaminants from water cheaply and effectively

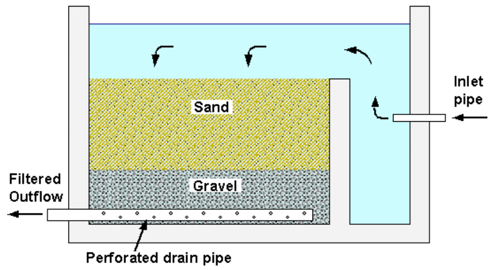
NanoSense
the basic sense behind nanoscience

Water Filtration Methods

There are simple and cheap ways to filter contaminants out of water

Sand, Gravel, and Charcoal Filtration

- **Pouring water through sand, gravel, or charcoal are simple and inexpensive methods of cleaning water**

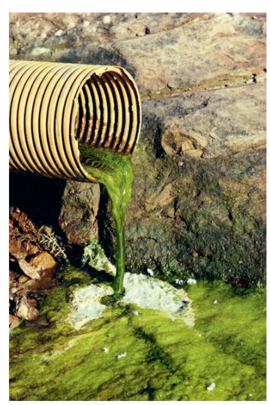


Sand and gravel filtration

Source: http://www.worldhungeryear.org/why_speaks/19_files/image014.gif

Small Contaminants Pass Through

- **Sand, gravel, and charcoal don't filter out some contaminants, like**
  - bacteria
  - viruses
  - industrial pollutants
  - agricultural pollutants
  - salt



Sources: http://www.liverpool.nsw.gov.au/LCC/INTERNET/RESOURCES/IMAGES/Water-pollution.jpg

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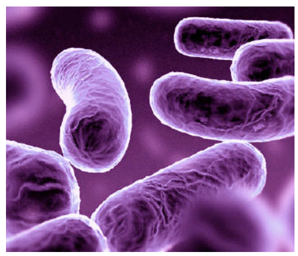
Question

How Can We Trap Smaller Contaminants?



Sources: http://www.turbosquid.com/FullPreview/Index.cfm/ID/274625

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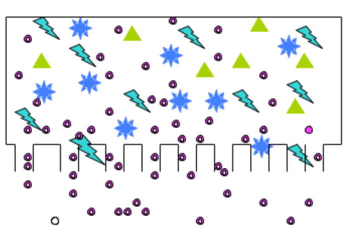
Membrane Filter Technology I

- A membrane is a thin material that has pores (holes) of a specific size
- Membranes trap larger particles that won't fit through the pores of the membrane, letting water and other smaller substances through to the other side



Membrane Filter Technology II

- **There are four general categories of membrane filtration systems**
  - Microfiltration
  - Ultrafiltration
  - Nanofiltration
  - Reverse Osmosis

Membrane Filter Technology III

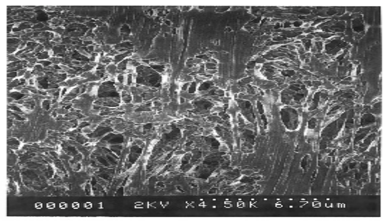
Filter type	Symbol	Pore Size, µm	Operating Pressure, psi	Types of Materials Removed
Microfilter	MF	1.0-0.01	<30	Clay, bacteria, large viruses, suspended solids
Ultrafilter	UF	0.01-0.001	20-100	Viruses, proteins, starches, colloids, silica, organics, dye, fat
Nanofilter	NF	0.001-0.0001	50-300	Sugar, pesticides, herbicides, divalent anions
Reverse Osmosis	RO	< 0.0001	225-1,000	Monovalent salts

Source: http://web.evs.anl.gov/pwmis/techdesc/membrane/index.cfm

Microfiltration

- **Typical pore size: 0.1 microns (10^{-7}m)**
- **Very low pressure**
- **Removes bacteria, some large viruses**
- **Does not filter**
  - small viruses, protein molecules, sugar, and salts

Microfiltration water plant, Petrolia, PA



A microfilter membrane

Sources: http://www.waterworksmw.com/rack%201%20&%202b.jpg http://www.imc.cas.cz/sympo/41micros/Image126.gif

Ultrafiltration

- **Typical pore size: 0.01 microns (10^{-8}m)**
- **Moderately low pressure**
- **Removes viruses, protein, and other organic molecules**
- **Does not filter ionic particles like**
  - lead, iron, chloride ions; nitrates, nitrites; other charged particles

An ultrafiltration plant in Jachenhausen, Germany

Source: http://www.inge.ag/bilder/presse/bildmaterial/referenzen/jachenhausen.jpg

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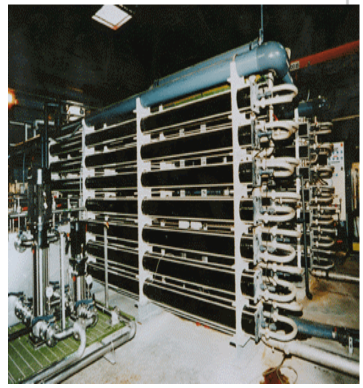
Nanofiltration

- **Typical pore size: 0.001 micron (10^{-9}m)**
- **Moderate pressure**
- **Removes toxic or unwanted bivalent ions (ions with 2 or more charges), such as**
  - Lead
  - Iron
  - Nickel
  - Mercury (II)



Nanofiltration water cleaning serving Mery-sur-Oise, a suburb of Paris, France

Source: http://www.wateronline.com/crlive/files/Images/10899070-E891-11D3-8C1F-009027DE0829/newwater1.gif

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Reverse Osmosis (RO)

- **Typical pore size: 0.0001 micron (10^{-10}m)**
- **Very high pressure**
- **Only economically feasible large scale method to remove salt from water**
  - Salty water cannot support life
  - People can't drink it and plants can't use it to grow

Reverse osmosis (or desalination) water treatment plants, like this one, are often located close to the ocean

Source: http://iclaro.com/users/18342/pictures/Desalination%20Plant.jpg

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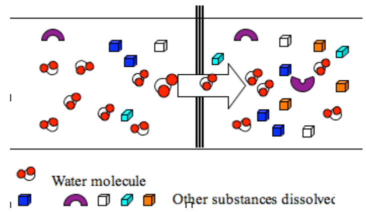
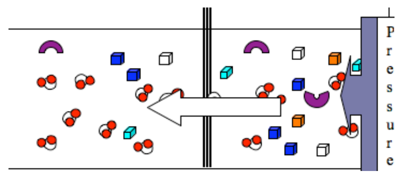
How RO Works

- Osmosis is a natural process that moves water across a semipermeable membrane, from an area of *greater concentration to an area of lesser concentration* until the concentrations are equal
- To move water from a *more concentrated area to a less concentrated area* requires high pressure to push the water in the opposite direction that it flows naturally



Osmosis



Reverse Osmosis

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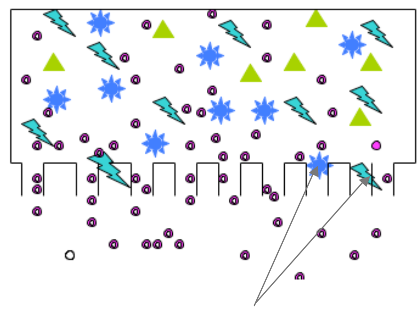
Question

If RO Can Get Everything Out That Would Make Water Undrinkable, Why Not Just Use RO Membranes by Themselves?

RO is Not for Everything!

- **High pressure is required to push the water through the smallest pores**
  - RO is the most $$$ filtration system
- **Because pores are so small, big particles can clog them (called fouling)**
  - This makes the filtering membrane unusable

Fouling of RO pores



Pores clogged with large objects

Question

How Can We Keep Large Particles from Fouling Membranes with Small Holes?

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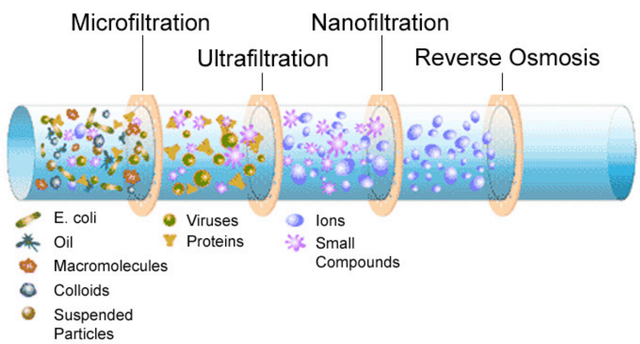
A Series of Filtrations Increases Efficiency

- **Filters can be sequenced from large to small pore size to decrease fouling**
  - They must still be cleaned regularly to remain usable



Source: Adapted from http://www.alting.fr/images/cross_flow_details.gif

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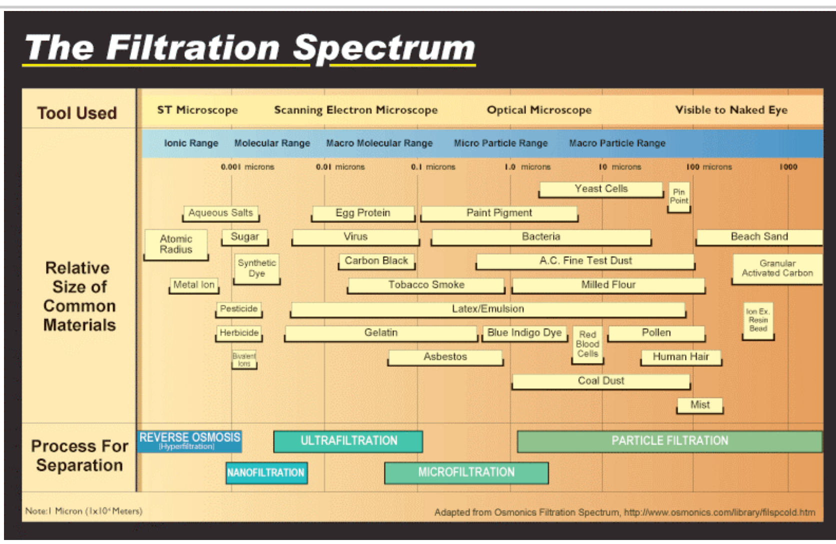
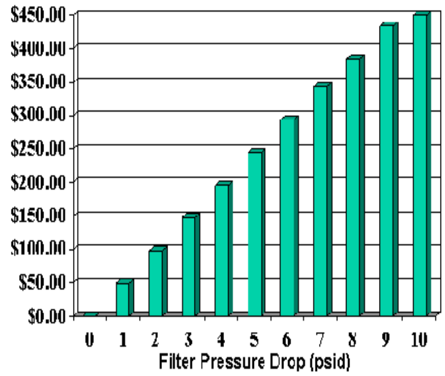
Water Filtration Chart



Source: Adapted from http://http://www.sasconsulting.ca/Files/Spectrum.jpg

Nanofiltration vs. Reverse Osmosis

- **Using RO to get rid of very small particles is very expensive**
  - Could we do it more cheaply?
- **Nanofiltration requires much less pressure than reverse osmosis**
  - Less pressure means lower operating costs!



What does this chart say about the cost of pressure used for filtration?

Source: http:/www.ecompressedair.com/images/library/kf_filter_f13.gif

Advantages of Nanofiltration

- **Nanofilters are close in size to RO filters, but cost much less to run**
- **And special properties of nanosized particles can be exploited!**
  - We can design new nanofilters that catch particles smaller than they would catch based on size alone
- **Scientists are exploring a variety of methods to build new nanomembranes with unique properties to filter in new and different ways**

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New Nanofilters are Unique!

- **Nanomembranes can be uniquely designed in layers with a particular chemistry and specific purpose**
  - Insert particles toxic to bacteria
  - Embed tubes that "pull" water through and keep everything else out
  - Signal to self-clean

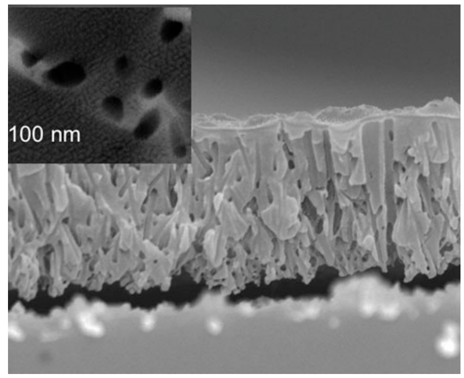

Image of a nanomembrane

Source: http://sciencematters.berkeley.edu/archives/volume2/issue10/images/story2-2.jpg

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New Nanomembranes I

- **Imagine having layers of membranes into which specialized substances are placed to do specific jobs**
  - You can put a chemical in the filter that will kill bacteria upon contact!

Chemicals toxic to bacteria could be implanted in nanomembranes

Source: Unknown

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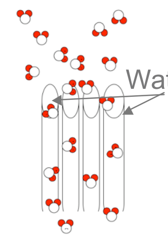
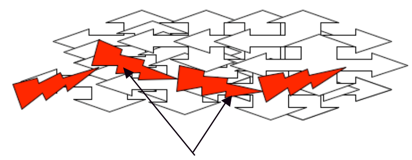
New Nanomembranes II

- **Embed "tubes" composed of a type of chemical that strongly attracts ("loves") water**
- **Weave into the membrane a type of molecule that can conduct electricity and repel oppositely charged particles, but let water through**





Electricity moving through a membrane

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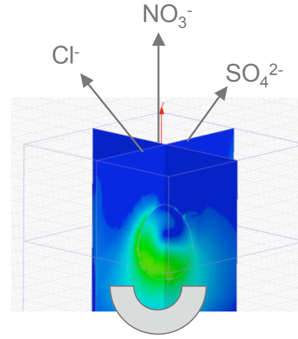
1 nm Sized Nanopores Repel Electronegative Objects

- **1-2 nm sized pores create an electric field over the opening**
  - This electric field is negative, and repels negatively charged particles dissolved in water
  - Most pollutants from agriculture, industry, and rivers are negatively charged
- **But water can get through!**



Representation of an electric field above a nanopore pushing away negative ions

Nanofiltration Summary

- **At the nanoscale, filters can be constructed to have properties designed to serve a particular purpose**
- **Scientists and engineers are now experimenting to create membranes that are low-cost yet very effective for filtering water to make it drinkable!**
- **These inventions may help to solve the global water shortage**

Questions

- **How do you determine what filtration method to use to remove contaminants in a water sample?**
  - Consider the size of the contaminants, the relative cost of the filtration methods, and the water use
- **What are two benefits that nanomembranes bring to the filtration of water?**
  - Consider how they can help to address the world's problem of a scarcity of clean drinking water
- **Describe three ways that current or experimental nanofiltration membranes may be different than previous generation membranes**

Nanofiltration: Teacher Notes

Overview

This set of slides provides some general background about the processes of water filtration. Common processes involve a sequence of filtrations through different kinds of membranes designed to remove different sizes of particles. Water is also often treated chemically, is sometimes irradiated, and even has substances added back into the water to improve its flavor. These slides give students a broad background in water filtration so that they can appreciate the innovations being explored by scientists and engineers who are designing nanomembranes for water filtration.

Slide 1: Title Slide

Slide 2: Water Filtration Methods

Removing contaminants to make water drinkable can be complex. Although the focus of this lesson is on membrane filtering technologies, there are simple and cheap methods for removing large contaminants in water, such as passing water through gravel, sand, and/or charcoal.

Slide 3: Sand, Gravel, and Charcoal Filtration

Students will be working with sand, gravel, and charcoal filtration in their lab activities. These are the very simple, inexpensive methods for cleaning large-sized contaminants out of water.

Slide 4: Small Contaminants Pass Through

However, sand, gravel, and charcoal filtration methods are not able to remove bacteria, viruses, and industrial or agricultural pollutants from water. If a water source has any of these contaminants, other filtration or cleaning methods must be used as well to produce safe drinking water.

Slide 5: How Can We Trap Smaller Contaminants? (Question Slide)

Have your students brainstorm ideas about ways to trap small contaminants like bacteria or viruses, which are not trapped by sand, gravel, or charcoal filtration.

Slide 6: Membrane Filter Technology I

This slide introduces students to the idea of a membrane blocking some (e.g., smaller) substances while allowing others to pass through. The basis of most membrane blockage is pore size. The size of the pore will determine what substances pass through the membrane and which ones remain on the other side.

Slide 7: Membrane Filter Technology II

This slide lists the four common types of membranes used for filtering water for drinking. There are many types of filters and methods of cleaning water, but this slide set focuses primarily on membrane technology, leading into a discussion of nanomembranes.

Slide 8: Membrane Filter Technology III

This is a quick overview that compares the four types of membrane filters on the basis of pore size, operating pressure, and type of substances that each of the membranes can remove. Students will look at these in more detail during the Cleaning Jarny's Water activity.

Slide 9: Microfiltration

The pore diameter of microfiltration membranes is typically in the range of 0.01 to 1.0 micrometers, with a typical diameter of 0.1 microns. Thus, microfiltration can be used to filter bacteria and some large viruses from water. It cannot filter out smaller contaminants like small viruses, proteins, molecules, sugar, and salts. The pressure required to push water through a microfiltration membrane is minimal. This slide shows a picture of a microfiltration water treatment plant and a close-up of a microfiltration membrane. You can see the pores in this membrane!

Slide 10: Ultrafiltration

Ultrafiltration can remove viruses, proteins, and other organic molecules from water using a moderately low amount of pressure. Ultrafiltration is an economical choice since not very much pressure is required to operate an ultrafiltration water treatment plant.

This slide would be a good place to point out that ions are charged particles that get dissolved into the water from natural and unnatural sources. Water, as a universal solvent, has the potential to dissolve small amounts of whatever the water passes over. Nitrates and/or nitrites and phosphates in excess in the water can be a sign of agricultural pollutant run-off.

Increased nitrates and/or phosphates in the water can lead to a series of events that ultimately cause a lake to lack sufficient nutrients to support fish life. At first, increased nitrates and phosphates provide basic nourishment to plants that will stimulate plant growth. Plant growth leads to an abundance of food for animals. Animal populations tend to increase as well when plant growth is surging. But too many animals in the water decreases the amount of dissolved oxygen, which is necessary for fish to live. Dead fish in the water decompose, providing nutrients for even more algae to grow. These events can lead to what is known as eutrophication, or a series of cause and effect events that lead to changing the ecosystem of a lake resulting in troubling impacts: decreased biodiversity and changes in the dominant species. This concept is not addressed at all within this lesson, but if appropriate, you may want to mention it.

Slide 11: Nanofiltration

This slide introduces "traditional" nanofiltration, which, like many of the other filtration technologies, has been around for decades. Later slides will talk about some of the new an innovative work occurring in the science and engineering of nanofilters.

Nanofiltration can remove bivalent ions (ions with more than one charge). Several nanofiltration plants have been built worldwide, but they are still relatively uncommon. This membrane technology is typically used when there is a limited amount of salt in the water.

Slide 12: Reverse Osmosis (RO)

Reverse osmosis (RO) is a membrane technology, about 35 years old, that can separate salt from water. RO membranes have essentially remained unchanged in recent decades. Though RO is the only known technology currently capable of desalinizing water, the process requires very high pressure, and is the most expensive membrane filtering system. Cities located by oceans are often good candidates for cleaning salt out of water.

Slide 13: How RO Works

As highlighted in the previous slide, reverse osmosis is the most successful and effective method of removing salt from water. These illustrations show how osmosis, a natural cellular process, pushes water across cell membranes by going in a direction that is more concentrated (and will therefore, be diluted when more water is added), until the concentrations are equal on both sides of the membrane. In our bodies, our kidneys perform this function.

Dialysis tubing is a common piece of lab equipment used in high school biology labs to demonstrate osmosis. Reverse osmosis goes in the “unnatural” direction, from the side that is more concentrated (without as many substances dissolved in the water) through the membrane to the side that is less concentrated. A great deal of pressure must be applied to push the water into an area less concentrated. The greater the pressure required to move the water through the filtration membrane, the higher it costs to operate the filtering system.

Slide 14: If RO Can Get Everything Out That Would Make Water Undrinkable, Why Not Just Use RO Membranes by Themselves? (Question Slide)

Have your students brainstorm about why RO by itself might not be the best solution. Ideas that they may entertain include: high cost (since RO requires high pressure), plugging of the RO membrane from large particles, and that not all water has salt in it that needs to be removed (e.g., fresh or lake water) so RO may be overkill in some cases.

Slide 15: RO is Not for Everything!

This slide points out that high pressure, high cost, and fouling are associated with using RO membranes. More pressure requires more energy use. Designing and maintaining (cleaning) a very small pore size is also very costly. You might point out that in the image, a few of the particles are blocking some of the pores.

Slide 16: How Can We Keep Large Particles from Fouling Membranes with Small Holes? (Question Slide)

Read the question posed on the slide out loud, and have your students brainstorm answers. Fouling can occur with every membrane filter system, when the pores of the filter become plugged with particulate matter that is larger than the pores.

The next two slides address this question, showing how filtering technology can occur in a step-wise fashion to optimize the more expensive filtration systems.

Slide 17: A Series of Filtrations Increases Efficiency

This slide illustrates the consecutive removal of increasingly small contaminants using a series of filters. It is less expensive to remove larger-sized contaminants with gravel, sand, or charcoal, and to use a series of increasingly smaller pore-sized membranes to remove increasingly smaller particles than to remove all sizes of particles with the membranes with the smallest sized pores. The filters would quickly foul and be in frequent need of cleaning. Using nanofiltration or RO to remove only small particles optimizes these expensive membranes for those sized particles that can only be filtered out of water by them.

Slide 18: Water Filtration Chart

This is a picture of the Filtration Spectrum: Student Handout that correlates the types of particles with their size, type of filter required to remove the particle from the water, and the type of microscope needed to view these sizes of particles. It illustrates the filtration methods that have been discussed so far. You might use the chart to quickly review the various methods that have been discussed.

Slide 19: Nanofiltration vs. Reverse Osmosis

This slide points out that RO can get rid of small particles, but it is expensive. Can we remove small particles more cheaply?

This graph demonstrates the correlation between the amount of pressure required and the cost of the water filtration system. The more pressure, the more energy is required, and the higher the operating cost.

Slide 20: Advantages of Nanofiltration

The pores in nanomembranes are close in size to those in RO filters, so can they be used more often as a cheaper alternative to RO? Yes, mainly due to recent advances in nanotechnology.

Nanomembranes have been around for decades, and were usually composed of a homogenous material throughout the fabric of the membrane. Recently, however, scientists have been able to build nanomembranes in layers, inserting substances with a particular chemistry and specific purpose. For example, new nanomembranes can not only filter based on *size* but also based on *charge*. In other words, the membrane can stop very small particles with a particular electrostatic charge while allowing water through.

Such advances have been made possible because of new tools and methods. Emphasize that engineering membranes to be uniquely designed for a specific purpose is a characteristic of nanofiltration and nanotechnology in general.

Slide 21: New Nanofilters are Unique!

Scientists can embed noxious substances in nanomembranes—substances that will kill bacteria on contact! Also, channels can be built into the membranes that are surprisingly hydrophilic, *attracting* water to pass through the membrane, thus reducing the pressure needed to *push* the water through it. Further, scientists envision creating membranes that are self-cleaning: a feedback mechanism initiates a chemical process that removes fouling residue. Using self-cleaning membranes could reduce both maintenance and operating expenses.

Benefits of nanomembranes are elaborated in more detail in the New Nanomembranes: Student Reading.

Slide 22: New Nanomembranes I

Eric Hoek talks about embedding particles into the membrane that are toxic to bacteria in the New Nanomembranes: Student Reading. When the bacteria combine with the toxic embedded substance, the bacteria die.

Slide 23: New Nanomembranes II

Two advances of new nanomembranes include the embedding of hydrophilic tubes through which water travels to the other side of the membrane, and the weaving of a conducting material through a membrane to repel oppositely charged particles.

Slide 24: 1 nm Sized Nanopores Repel Electronegative Objects

Eric Hoek explains this idea in the New Nanomembranes: Student Reading. This discovery was made serendipitously when constructing membranes with 1 to 2 nanometer pores.

Slide 25: Nanofiltration Summary

This slide concludes the introduction of how nanomembranes can be used to filter contaminants out of water. Hopefully students have gained an appreciation for how nanomembranes can be built with selected properties by embedding them with specialized materials. Nanomembranes hold the promise of a new generation of water filtration membrane technology.

Slide 26: Questions for Discussion

This final slide poses further questions for discussion that are related to this lesson. You may want to ask students to discuss their ideas aloud or in writing, to reinforce the central concepts.

Which Method is Best? Teacher Instructions & Answer Key

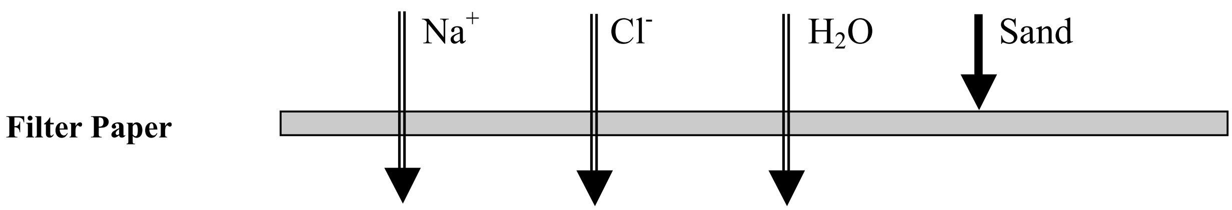
Purpose

Use the Filtration Spectrum: Student Handout to determine which filtration method is best suited to filter a variety of particles.

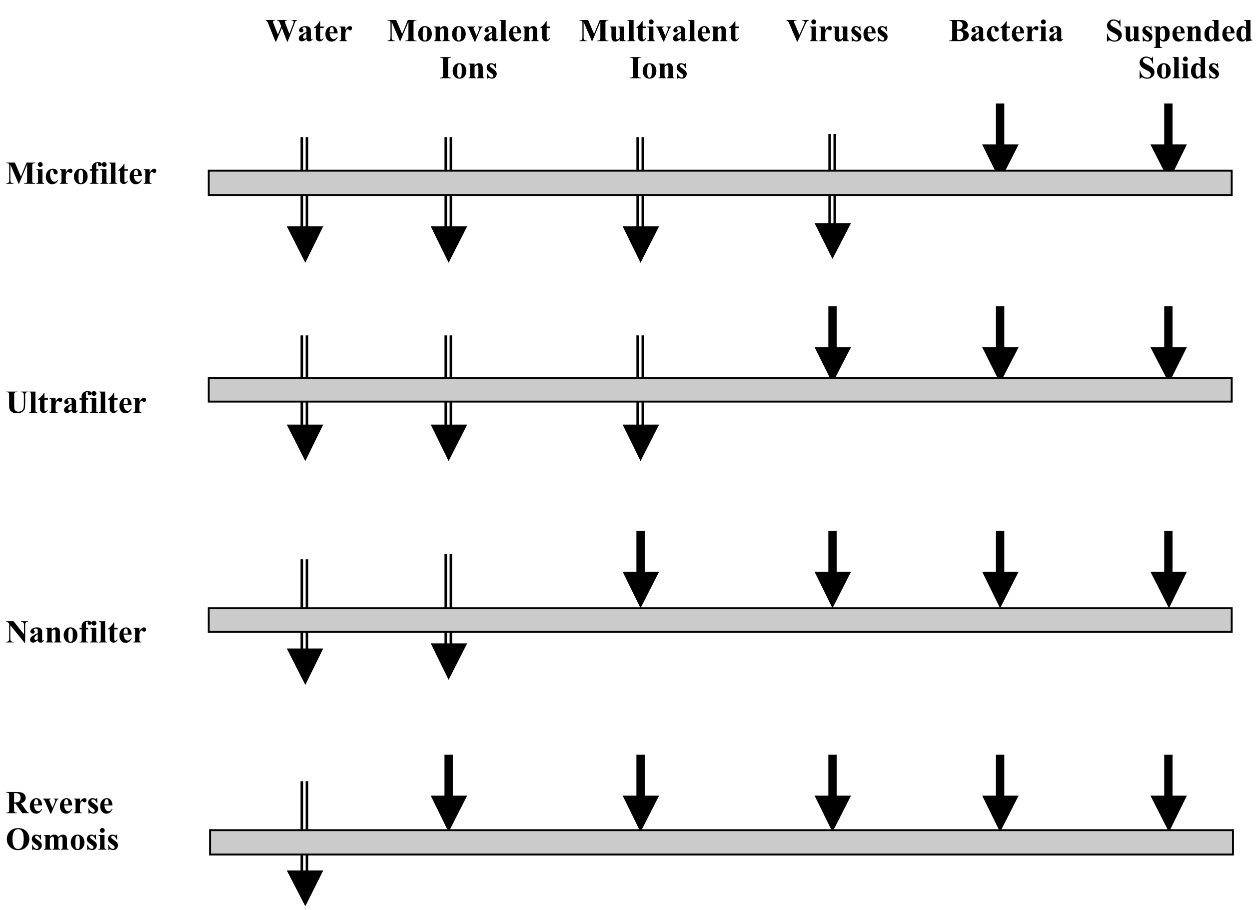
The goal is to have students actively use the information in the handout to become familiar with the limitations of each filtration method. This exercise will also help students visualize the transport of particles, and not others, through different membranes.

Introduction and Example

If you had a filter that was made of paper, it would not let sand pass through but would allow water and dissolved sodium chloride pass through. To demonstrate this, you would draw the following arrows:



Refer to the Filtration Spectrum handout. Based on what you see in the handout, draw arrows that show which particles will pass through each membrane and which will not.



Comparing Nanofilters to Conventional Filters Lab Activity: Teacher Instructions

This lab activity demonstrates the concept of filtration as a means of separating a variety of substances from water using a variety of filtration techniques (Part I), and then compares ultrafiltration with nanofiltration (Part II). In particular, students will observe and test "river water" to identify the substances mixed and dissolved into the water, and then run the water through a series of filtration systems, ending with nanofiltration. They will perform chemical tests and make visual observations to determine if the substances originally identified in the water remain in solution after using various filtration techniques, and report their results on lab sheets.

If you have already conducted this type of investigation using filtration, you may go directly to Part II, comparing ultrafiltration with nanofiltration. Rather than creating the "river water" and testing it according to the directions specified below, you may simply want to purchase a water-testing kit and collect your own sample of river water (pond water, lake water, etc.).

The company Argonide manufactures and sells a nanofiltration kit that contains everything that you need for the nanofiltration activities in this lab. To purchase, contact:

> Henry Frank, Sales and Marketing Manager
> Argonide Corporation (www.argonide.com)
> 291 Power Court, Sanford, FL 32771-1943
> Email: henry@argonide.com, Tel: 407-322-2500, Fax: 407-322-1144

with this order information:

> Product #: MTK-SRI
> Description: NanoCeram Media Test Kit (complete)
> Price: 1-10 kits: $216.50/kit; 11-49 kits: $201.84/kit; 50+ kits: $187.19/kit.

Overview

You are on a backpacking trip in the mountains with a friend. Each of you has brought 2 liters of water with you and you are running very low. You had planned to stay at least for another day, but realize that if you don't find a source of clean drinking water, you will need to turn back and end your trip early. You brought with you some water testing strips and a nanofilter that fits inside of a syringe, just in case you needed to drink the water from the river. Your job is to use your testing strips to find out what else, besides what you can see (such as leaves) is in the water. Once you find what is in the water, you will have to filter out any of the unwanted substances.

The pores of your nanofilter are so small that they will easily plug with large substances. You want to filter as much as you can using the gravel and the sand by the river in a funnel. You have also brought activated charcoal with you.

Can you make the river water clean enough to drink, or do you have to turn around and go home?

Materials for Each Station: Filtration (Part I)

- ½ cup sand
- ½ cup gravel
- About 50 mL of activated charcoal
- 1 25 mm NanoCeram® nanofilter disc
- 1 Luer-Loc filter housing (to hold the nanofilter)
- 2 250 mL beakers
- 1 funnel
- Paper towels
- Syringe
- Test strips for nitrate and nitrite ions
- Test strips for chloride ions
- Test strips for copper
- Test strips or drops for iron(II) and iron(III) ions
- ½ liter of "river water" in a bottle

Materials to Make 1.0 Liter of "River Water" for Two Lab Stations

- 2 half-liter bottles
- 1 liter of distilled water
- ½ teaspoon salt
- A few crushed leaves
- 3 pinches of dirt
- 2 pinches of sand
- 2 teaspoons table salt
- 2.5 mL *No More Algae* liquid by Jungle, 0.05% (by volume) copper sulfate pentahydrate (source of copper liquid)
- 1 crushed tablet of Fe (27 mg) purchased at a drug or grocery store

Materials for Each Station: Comparing Ultrafiltration with Nanofiltration (Part II)

- 1 25 mm NanoCeram® nanofilter disc
- 1 25 mm Millipore VS ultrafilter disc
- 1 Luer-Loc filter housing (to hold the nanofilter and the ultrafilter)
- Syringe
- Bottle of water containing dissolved dye
- (2) small effluent collectors

- Paper towels

Procedures: Filtration (Part I)

Mix together all of the river water ingredients and pour into two half-liter bottles.

Distribute river water and materials to each lab station, and post the student instructions at each lab station for students to follow.

Each student should have their own lab sheet for recording their data and answering questions.

Setup

1. Put the charcoal in water to soak for at least 10 minutes, and proceed with the next step. After 10 minutes, take the charcoal out and rinse it thoroughly to prevent coloring the water.
2. Arrange the ring on the ring stand and put the empty funnel inside of the ring, as shown in Figure 1. Put the 250 ml beaker underneath the funnel so it will catch the effluent.
3. Look at the river water in the bottle. Record your observations of the river water on your lab sheet. Be sure to notice texture, colors, and anything else that stands out.
4. Follow the instructions in the Ion Testing box below to test the river water for the presence of the ions.

Figure 1. Funnel supported by ring with beaker underneath to catch effluent [1].

Ion Testing

1. Label a paper towel with each of the symbols of the ions you will test:
   Fe^{2+} Fe^{3+} Cl^- NO_3^- NO_2^- Cu^{2+}
2. Dip the appropriate strips in the river water to test for these ions.
3. Put the wet strips on a paper towel under their appropriate symbols so you don't forget which strip represents a test for which ion.
4. Match the color of your strip with the color chart on the side of the relevant test strip bottle. The amount of the ion in your river water sample will be listed underneath the matching color square on the bottle.
5. Record on your lab sheet the color of the strip and the amount of each ion indicated by the test strip.

You will repeat this “ion testing” step after each filtration to find out if the ions are still present in the water.

Table 1 summarizes the consequences of the presence of these ions in drinking water.

Table 1. Ions and Consequences in Drinking Water

Ions	Consequences in Drinking Water
Fe^{2+} and Fe^{3+}	These ions indicate that rust from pipes has gotten into the water. While rust is not dangerous, it makes the water taste bad and leaves mineral deposits in sinks and bathtubs.
NO_3^- and NO_2^-	These ions are an indication that pesticides from agriculture have gotten into the water.
Cl^-	This ion indicates that salt has intruded into the water. People cannot use salty water for drinking. Salty water usually cannot be used for agriculture either, although there are a few exceptions.
Cu^{2+}	Copper is normally found in water from natural sources as well as from corrosion of the copper pipes used for water. Copper is not harmful in quantities less than 1000-μm.

Gravel Filtration

1. Put ½ cup of **gravel** into the funnel.
2. Put a clean 250 mL beaker underneath the funnel.
3. Pour the river water supplied by your teacher over the gravel. Notice if the gravel stopped any of the substances that you saw in the water from going into the beaker below.
4. Record your observations on your lab sheets.

Gravel and Sand Filtration

5. Put ½ cup of **sand** on top of the gravel in the funnel.
6. Put a clean 250 mL beaker under the funnel.
7. Pour the contents of the first beaker, the effluent, into the funnel on top of the sand. Notice if the sand and gravel stop any of the substances in the water from going into the beaker below.
8. Record your observations on your lab sheet.
9. Rinse the empty 250 mL beaker and place it underneath the funnel.

Gravel, Sand, and Activated Charcoal Filtration

10. Put the **activated charcoal** into the funnel on top of the sand and the gravel.
11. Pour the remaining water (the effluent) left from the sand filtration step into the funnel on top of the charcoal. Notice if the charcoal removes anything else.

12. Record your observations on your lab sheet.

Conduct Ion Test

13. Using the test strips, test for the presence of the ions in the filtered water by following the instructions in the Ion Testing box above.
14. Record the results of your ion tests on your lab sheet and answer the questions.

Nanofiltration

15. Get a 25 mm NanoCeram® nanofilter disc and a Luer-Loc ceramic filter housing.
16. Open the filter housing and carefully place the disc into the filter housing, place the O-ring on top of the disc, and close securely, making sure the disc is centered in the housing to prevent leakage around the edges of the disc.
17. Rinse the empty 250 mL beaker and place it underneath the filter.
18. Fill the syringe with the effluent collected after filtering with the charcoal, sand, and gravel.
19. Screw the filter housing onto the syringe, taking care not to depress the plunger of the syringe during this operation.
20. Push the effluent through the nanofilter using even, steady pressure.
21. Record your observations of the solution after it has gone through the nanofilter on your lab sheet.

Conduct Ion Test

22. Using the test strips, test for the presence of the ions in the filtered water by following the instructions in the Ion Testing box above.
23. Record the results of your ion tests on your lab sheet and answer the questions.

Procedures: Comparing Ultrafiltration with Nanofiltration (Part II)

You have just used a new nanofilter (the NanoCeram filter) that has recently come to market. An older ultrafilter, called the Millipore VS filter is also available. The NanoCeram® filter is a multilevel woven membrane with various nanoparticles embedded into the layers of membranes. The Millipore VS membrane is a nonwoven, matte-like paper.

The purpose of this part of the lab activity is to compare the nanofilter with the ultrafilter based upon the following two criteria:

- Completeness of filtration
- The relative amount of pressure needed to push the water through each filter

The completeness of filtration will be measured by filtering dissolved dye through each of the filters and looking at the color of the filter and the effluent. The relative pressure needed for filtration will be measured by how hard you have to push the syringe to get the water to pass through the filters.

Compare Millipore VS and NanoCeram® Filtration

1. Open the bottle containing the dissolved dye and draw 2-3 mL into the syringe.
2. Open the Luer-Loc filter housing and carefully place a single 25mm disc of **Millipore VS** membrane material into it. Place the O-ring on top of the disc and close securely, making sure the disc is centered in the housing to prevent leakage around the edges of the disc.
3. Screw the filter housing onto the syringe, taking care not to depress the plunger of the syringe during this operation.
4. Depress plunger of the syringe while holding the syringe over an effluent collector to capture the fluid as it exits the syringe through the filter housing.
5. Apply enough pressure to ensure that the dissolved dye is passing through the filter media. *Typical results for this stage using the Millipore VS membrane material show only several drops coming out of the syringe due to the extreme amount of pressure required to force the dissolved dye through the filter.*
6. Once this is completed, carefully remove and open the filter housing, and remove the filter membrane.
7. Place the membrane aside, next to the effluent collector containing the effluent from this test.
8. Rinse the syringe and repeat the sequence of steps 1-7 above, but with the **NanoCeram®** filter. Push the dissolved dye through gently and steadily; avoid pushing fast.
9. Compare the color of the effluent from the two filters, the color of the filters, and how easy or hard it was to push the dissolved dye through the filters with the syringe.
10. Record your observations on your lab sheet.
11. Answer the questions on your lab sheet.
12. Clean your lab station.

References

(Accessed January 2008.)

[1] http://icn2.umeche.maine.edu/newnav/newnavigator/images/P7280072.JPG

Cleaning Jarny's Water: Teacher Instructions & Answer Key

This problem-solving activity is based on a real world story about the water of Jarny, France. A problem scenario is presented in which students use data to compare Jarny water quality (i.e. levels of substances) with Environmental Protection Agency fresh drinking water standards. Students will determine which substances need to be filtered from the water to make it safe to drink. Students are asked to design one or more additional water filters to make the water safe to drink for the people of Jarny.

Students may use The Filtration Spectrum: Student Handout, which shows particle size, particle type, and appropriate filtration system as a resource to guide their work. It is recommended that the students work in heterogeneous ability groups of three or four and that they share with the class the water filtration systems that they have designed.

There's a Problem with Our Water…

In the Eastern part of France, in the city of Jarny (see Figure 1), the local people have a serious problem with their drinking water. Their main source of drinking water comes from the ground water table located near an old iron mine. (See Figure 2 for an explanation of ground water.)

The water has always been pumped out of the mine and filtered before being used for drinking water. When the mine was active, this system worked fine. But since closing, the water has flooded up into the mine, creating a pool of standing water that seeps into the ground water used for drinking.

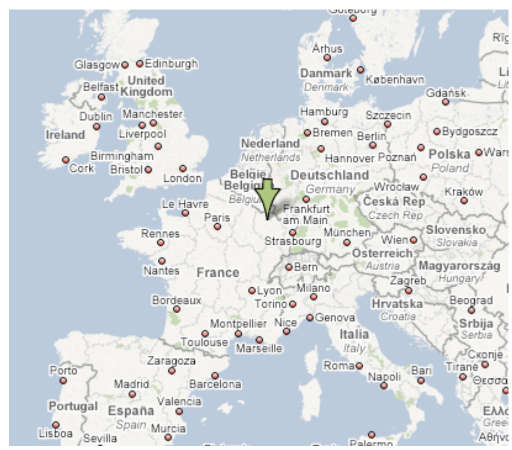


Figure 1. Jarny, France (green arrow) [1].

Over time, the water sitting in the mine reacted with the debris left in the abandoned mine, leaving much of the water contaminated. A local water-monitoring agency has watched the rising contamination levels and determined that the current water cleaning system is not good enough to make the water safe to drink. Even before the water flooded up into the mine, a few substances were slightly above safety limits, but now their levels are even higher.

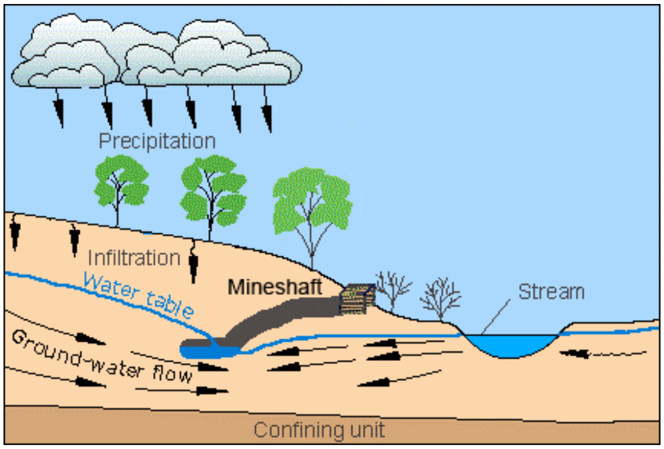


Figure 2. Ground water [2].

Water that comes from rain (precipitation) trickles through the ground (infiltration) until it flows to an area that it can't pass through, such as bedrock. Fresh water accumulates in these places and is referred to as *ground water*. The top of the ground water is the water table. When this underground water is large enough, it is called an aquifer. Aquifers are a commonly used source of fresh drinking water for people all over the world.

Now that you have some background on the water problem facing Jarny, your team's job is to design a system to clean the water to make it drinkable by the local residents. To do this you will need to do the following:

1. Analyze the data in Table 1 to identify what harmful substances are present in the water. This table provides raw water measurements on a set of substances, selected due to their change in concentration before and after the flooding.
2. Complete question 1 in the Student Report. Record the following information for each substance:
    - The name of the substance identified to be filtered out of the water
    - The amount the substance is over the acceptable limit
    - The ranking of substances by size (1 = largest)
    - The least expensive filter needed to filter the substance identified
3. Analyze the data on the current water cleaning system (Table 2), your reading handouts, and relevant charts to help inform your design of a system to clean the water to make it drinkable. Assume that your design will be added on to the system currently in place: a flocculation procedure, a sand filter, and a 1.0 micron microfilter. Remember that the town is poor and your design needs to provide a cost-effective solution. Your design may involve single-step or multiple-step methods.
4. Complete questions 2 and 3 in the Student Report.

Table 1. Water Measurements Before and After Flooding

Substance	Before flooding (mg/L)	After flooding (mg/L)	"Safe" levels (mg/L)	Health hazard or water-taste quality
Ca^{2+}	168	296	160	Contributes to water "hardness"
Mg^{2+}	31	185	15	Contributes to water "hardness"
Na^{+}	50	260	350	Dehydration
CO_3^{2-}	367	500	100	Taste or alkalinity
SO_4^{2-}	192	1794	300	Water taste
Cd^{2+}	.002	.018	.005	Kidney damage
Bacteria (*E. coli*)	0	24	0	Diarrhea, cramps, nausea, or headaches
Asbestos (million fibers/L) from rotting pipes	2	12	7	Increased risk of developing intestinal polyps
Human hair (million hairs/L)	16	48	3	None known, just disgusting

Table 2. Jarny's Current Water Cleaning System

Jarny's current water cleaning system involves treating the water with a flocculent (a material that combines with large-sized particles in the water) and then letting the flocculent (with the large particle combinations) sink to the bottom so it can be removed. The remaining water is filtered through two filters: 1) sand, and then 2) a membrane with 1.0 micrometer diameter holes.

References

[1] http://maps.google.com

[2] Adapted from http://ga.water.usgs.gov/edu/earthgwdecline.html

Student Report

1. Use the water quality information in Table 1 to fill in Table 3 below.

Table 3. Substances Present at Unacceptable Levels

Substance	Amount over acceptable limit	Rank substances by size (1=largest) If there is a range, choose the size at the smallest end of the range Particles of similar size can have the same ranking	Least expensive filter necessary
Ca^{2+}	136 mg/L	4	nanofilter
Mg^{2+}	170 mg/L	4	nanofilter
CO_3^{2-}	400 mg/L	4	nanofilter
SO_4^{2-}	1494 mg/L	4	nanofilter
Cd^{2+}	0.013 mg/L	4	nanofilter
Bacteria (*E coli)*	24	2	microfilter
Asbestos	5	3	ultrafilter
Human hair	45 (between 40-300 microns)	1	particle filter

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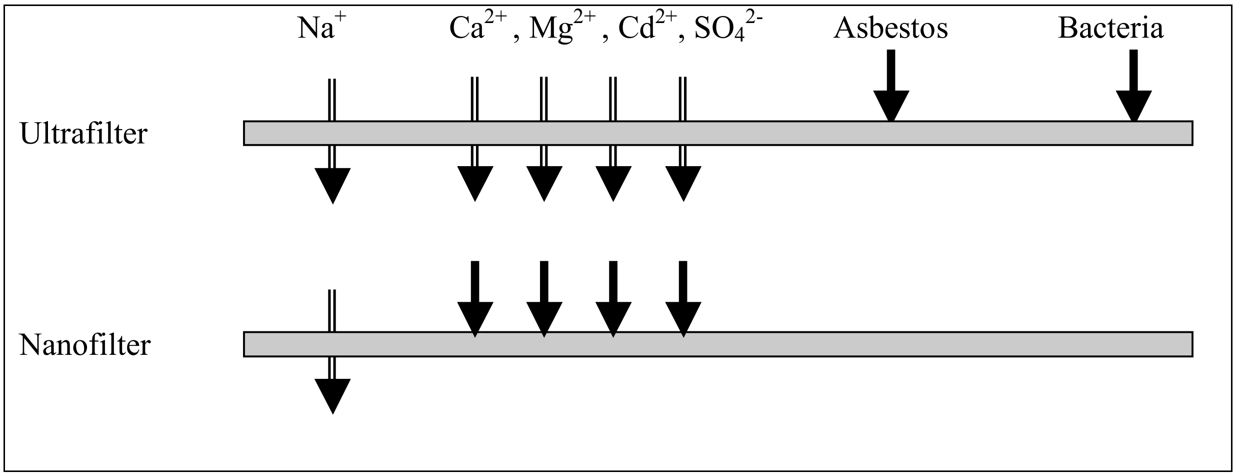
2. The best filter or combination of filters to add to Jarny's water system are the following, in order:

A ultrafilter (filter with a pore size of < 0.1 microns) and then a nanofilter.

3. Draw your design showing the water and its contents before and after passing through each filter in your design.



Reflecting on the Guiding Questions: Teacher Instructions

You may want to have your students keep these in a folder to use at the end of the unit, or collect them after each lesson to see how your students' thinking is progressing.

Think about the activities you just completed. What did you learn that will help you answer the guiding questions? Jot down notes in the spaces below.

1. Why are water's unique properties so important for life as we know it?

What I learned in these activities: What I still want to know:

2. How do we make water safe to drink?

What I learned in these activities: What I still want to know:

3. How can nanotechnology help provide unique solutions to the water shortage?

What I learned in these activities: What I still want to know:

4. Can we solve our global water shortage problems? Why or why not?

What I learned in these activities: What I still want to know: