

Module 3: Effects of Nuclear Explosions

Topics covered in this module —

- Weapons of mass destruction
- Overview of weapon effects
- Effects of thermal radiation
- Effects of blast waves
- Effects of nuclear radiation
- Possible effects of nuclear war

Effects of Nuclear Explosions

“Weapons of Mass Destruction”

“Weapons of Mass Destruction”

Even a simple fission device can release *a million times* more destructive energy per kilogram than conventional explosives.

Nuclear weapons are the only weapons that could —

- Kill millions of people almost instantly
- Destroy the infrastructure and social fabric of the United States

Chemical and biological weapons do not have this capacity.

Only nuclear weapons are “weapons of mass destruction”

Only nuclear weapons threaten the survival of the U.S.

Radiological Weapons

A radiological weapon is a device that spreads radioactive material.

Such a weapon is a weapon of mass *disruption*, not mass *destruction*.

Dispersal of a substantial quantity of highly radioactive material in a city would *not* —

- physically damage structures
- immediately injure anyone

It could —

- contaminate a few city blocks with highly radioactive material
- contaminate a larger area with more weakly radioactive material

If explosives were used to disperse the material, the explosion could cause a small amount of damage and some injuries.

Depending on their exposure to radiation and how they were treated afterward —

- 100s or perhaps even 1,000s of people could become sick
- a larger number could have a somewhat higher probability of developing cancer or other diseases later in life

The main effect would be to create fear and disrupt normal activities.

Chemical Weapons

A chemical weapon is a device that releases toxic chemicals.

Release of toxic chemicals in a city would not cause mass destruction but would —

- create fear
- disrupt normal activities
- possibly cause a large number of casualties.

The most deadly chemicals, such as nerve gases, are complicated to synthesize, extremely dangerous to handle, and difficult to use effectively.

A complex long-term effort would be needed to develop and effectively deliver such an agent.

If dispersed effectively, a chemical agent could contaminate a substantial area.

If toxic enough, it might cause 100s or even 1,000s of casualties, but it would not destroy buildings or vital infrastructure.

Precautions before and rapid medical treatment and decontamination after such a release would reduce substantially the number of casualties, especially for less deadly agents.

Biological Weapons

Release of a biological agent would create fear and disrupt normal activities, but would not cause mass destruction.

In order to cause mass casualties, substantial amounts of agents such as anthrax, smallpox, and plague would have to be converted into tiny particles and then dispersed in an aerosol.

Because these agents are so deadly, the required forms and the equipment needed to disperse them are difficult to come by.

A complex long-term effort would be needed to develop and effectively deliver such an agent.

A pathogen such as anthrax that does not produce contagious disease could be used to attack a particular building or area.

A pathogen such as smallpox that produces a deadly contagious disease would be a “doomsday” weapon, because it could kill millions of people worldwide, including the group or nation that released it.

In countries with an effective public health service, prompt quarantine, vaccination, and other measures could reduce greatly the number of casualties, the area affected, and the time required to get the disease under control.

In less-developed countries, a contagious deadly disease could be devastating..

Nuclear Weapons

In contrast to a chemical or biological agent, a “small” (10 kiloton) nuclear weapon detonated in a major city would kill more than 100,000 people and reduce tens of square kilometers to rubble almost instantly.

Even a crude nuclear device that fizzled would destroy many square kilometers of a city and kill tens of thousands of people.

A large (1 megaton) nuclear weapon could kill millions of people and destroy hundreds of square kilometers within a few seconds.

Those who survived a nuclear explosion would have to deal with severe physical trauma, burns, and radiation sickness. Vital infrastructure would be destroyed or damaged, and radioactivity would linger for years near and downwind of the explosion.

Unlike the effects of a chemical or biological weapon, the devastating effects of a nuclear weapon on a city cannot be reduced significantly by actions taken before or after the attack.

Why “Weapons of Mass Destruction”?

In recent years some have sought to lump together as “WMD”—

- radiological weapons (“dirty bombs”)
- chemical weapons
- biological agents
- nuclear weapons

Broadening the definition of “WMD” and using it in this way had two main purposes:

- To make nuclear weapons seem no different from other weapons
- To make chemical and biological weapons seem as dangerous as nuclear weapons and therefore a justification for war or even nuclear war

This was politically motivated and obscures the profound differences in

- lethality and destructiveness
- timescales on which their effects are felt
- the possibility of protecting against them (or not)

In Physics 280, we will avoid the term “WMD”. Instead, we will say what we mean: “nuclear weapons”, “chemical weapons”, or “biological weapons”.

Physics 280: Session 9

Plan for This Session

Student questions, news, and discussion

iClicker questions soon and later in the class

Module 3: Effects of nuclear explosions (cont'd)

Session 9: News and Discussion

The CHRISTIAN SCIENCE
MONITOR

Horizons

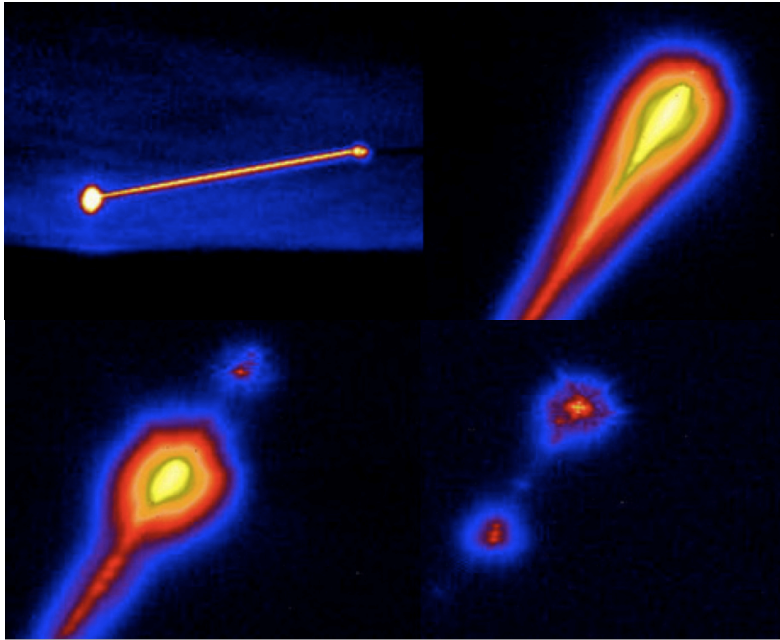
Airborne laser shoots down missile in mid-flight

By Chris Gaylord

posted February 12, 2010 at 3:58 pm EST

Last night, the military officially entered the age of airborne laser weapons. A large laser mounted to the front of a modified 747 jet successfully detected and shot down a ballistic missile while both were in mid-flight.

Session 9: News and Discussion



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Credit: gizmodo.com

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Session 9: News and Discussion

Ex-senator Nunn warns of nuclear terror threat

By Tom Sabulis
The Atlanta Journal-Constitution

9:56 a.m. Monday, February 15, 2010

It's probably a safe bet that former U.S. Sen. Sam Nunn (D-Ga.) has never been mistaken for a movie star, yet he plays a central role in one of the world's biggest potential dramas: keeping nuclear weapons out of the hands of terrorists.



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Session 9: News and Discussion

As co-chairman and CEO of the Nuclear Threat Initiative, a nonprofit organization working to curtail weapons of mass destruction, Nunn, 71, gets his share of camera time in the new documentary, "Nuclear Tipping Point," along with former Secretaries of State Henry Kissinger and George Shultz and former Defense Secretary William Perry. The foursome tackles the escalating risk of a deadly terrorist strike.

The documentary is available for free through the Web site nucleartippingpoint.org and free public screenings are being set up around the country.

Session 9: News and Discussion

Q: Is it going to take some kind of nuclear near-miss to get this topic on the radar of the public at large?

A: I hope not. The public consciousness of the changing threat has really gone up in the last several years. When we started our Nuclear Threat Initiative 10 years ago, it basically was not on the radar at all. The more countries that get nuclear weapons, or even the more countries that go into enrichment, like the Iranians have now, the more likely it is that we'll have a group of people with no return address getting enough material [for] a nuclear weapon.

Session 9: News and Discussion

Q: How dire is the situation?

A: As I view the threat, we have a perfect storm. We have weapons of mass destruction-type material spread in at least 40 countries around the globe. We have technological know-how that is spread very wide now. It was formerly thought that only a state could make a bomb; nobody that's informed on the subject believes that any more. We've got an increasing number of terrorists who would not hesitate to use a nuclear weapon if they were able to get one.

And now we've got the spread of enrichment technologies.

Session 9: News and Discussion

Q: Is the thinking that if terrorists got their hands on a bomb they would automatically use it?

A: I think they'd probably do it in a calculating way. My worst case [scenario] is, they would set off one explosion. It would be a crude weapon; it wouldn't come in on a missile. It would probably come in on the back of a truck to a city. And if one went off and killed hundreds of thousands of people, they'd basically probably announce they had six or eight more in cities around the country or around the globe. That would have huge devastating impact, certainly on the people who were the original victims, but also the whole world economy. You'd have people dumping out of cities all over the world like nothing we've ever seen.

iClicker Question

How does the power of the (primitive) Hiroshima nuclear weapon compare with the power of a large conventional (high-explosive) weapon?

- A. About the same
- B. 10 times more
- C. 100 times more
- D. 1,000 times more
- E. 1,000,000 times more

Blank

iClicker Answer

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iClicker Question

What are the three stages of a large thermonuclear bomb?

- A. fission-fission-fission
- B. fission-fission-fusion
- C. fission-fusion-fission
- D. fusion-fission-fusion
- E. fusion- fusion -fusion

Blank

iClicker Answer

What are the three stages of a large thermonuclear bomb?

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- B. fission-fission-fusion
- C. **fission-fusion-fission**
- D. fusion-fission-fusion
- E. fusion- fusion -fusion

Effects of Nuclear Explosions

Overview of Nuclear Explosions

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Effects of Nuclear Explosions

Read and Study

The Day After Midnight

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Effects of Nuclear Explosions (Overview)

- Effects of a single nuclear explosion

- Prompt nuclear radiation
- Electromagnetic Pulse (EMP)
- Thermal radiation
- Blast wave
- Residual nuclear radiation (“fallout”)
- Secondary effects (fires, explosions, etc.)



- Possible additional effects of nuclear war

- World-wide fallout
- Effects on Earth’s atmosphere and temperature
- Effects on physical health, medical care, food supply, transportation, mental health, social fabric, etc.

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Number of Fissions When a Nuclear Weapon is Exploded

Generation	Fissions in the generation	Energy released
1	$2^0 = 1$	
2	$2^1 = 2$	
3	$2^2 = 2 \times 2 = 4$	
4	$2^3 = 2 \times 2 \times 2 = 8$	
5	$2^4 = 2 \times 2 \times 2 \times 2 = 16$	
10	$2^9 = 512$	
30	$2^{29} = 5.3 \times 10^8$	
70	$2^{69} = 5.9 \times 10^{20}$	2.5×10^{-4} Y
79	$2^{78} = 3.0 \times 10^{23}$	0.12 Y
80	$2^{79} = 6.0 \times 10^{23}$	0.25 Y
81	$2^{80} = 1.2 \times 10^{24}$	0.50 Y
82	$2^{81} = 2.4 \times 10^{24}$	1.00 Y

Each generation lasts about 1 “shake” = 10^{-8} sec = 1/100,000,000 sec.
 All 82 generations last 82×10^{-8} sec = 0.8×10^{-6} sec \approx 1 microsecond.

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Energy Released in a Nuclear Explosion (Review)

The total energy released is the “yield” Y

Y is measured by comparison with TNT

By definition —

- 1 kiloton (kt) of TNT = 10^{12} calories
- 1 Megaton (Mt) of TNT = 1,000 kt = 10^{15} calories

1 calorie = the energy required to heat 1 gram of H_2O by
1 degree Celsius (C) = 4.2 J

(1 dietary Calorie [Cal] = 1,000 calories = 1 kcal.)

Initial Distribution of Energy From Any Nuclear Explosion (Important)

After ~ 1 microsecond —

- Essentially all of the energy has been liberated
- Vaporized weapon debris has moved only ~ 1 m
- Temperature of debris is $\sim 10^7$ C (\sim center of Sun)
- Pressure of vapor is $\sim 10^6$ atmospheres

The energy is *initially* distributed as follows —

- Soft X-rays (1 keV) $\sim 80\%$
- Thermal energy of weapon debris $\sim 15\%$
- Prompt nuclear radiations (n, γ , e^-) $\sim 5\%$

Subsequent Evolution of Nuclear Explosions

What happens next depends on —

- The yield of the weapon
- The environment in which the energy was released

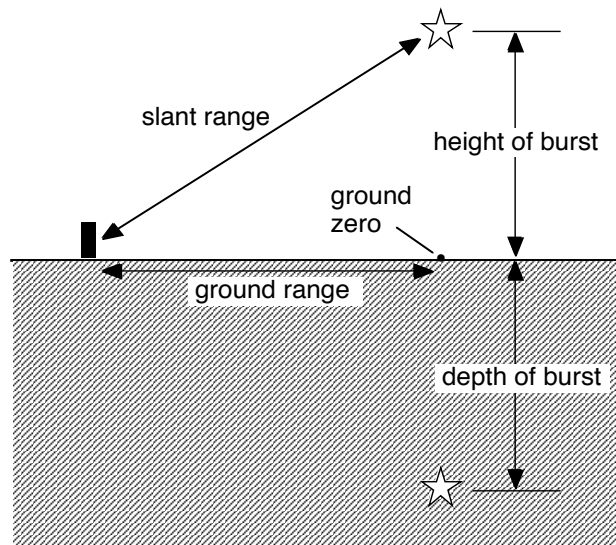
It is largely independent of the weapon design.

Nuclear Explosions

Possible environments —

- Explosions in space
- Explosions at high altitude (above 30 km)
- Air and surface bursts
- Underground
- Underwater

Nuclear Explosion Geometries



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Nuclear Explosions in Space

The U.S. exploded nuclear weapons in space in the late 1950s and early 1960s —

- Hardtack Series (Johnston Island, 1958)
 - Teak (1 Mt at 52 miles)
 - Orange (1 Mt at 27 miles)
- Fishbowl Series (1962)
 - Starfish (1.4 Mt at 248 miles)
 - Checkmate (sub-Mt at tens of miles)
 - Bluegill (sub-Mt at tens of miles)
 - Kingfish (sub-Mt at tens of miles)

Led to discovery of EMP and damage to satellites by particles trapped in the geomagnetic field

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Underground Nuclear Explosions

Fully contained (no venting) —

- No debris from the weapon escapes to atmosphere
- No ejecta (solid ground material thrown up)
- Subsidence crater may form in hours to days
- No radioactivity released (except noble gasses)
- Characteristic seismic signals released

Partially contained (some venting) —

- Throw-out crater formed promptly (ejecta)
- Radiation released (mostly delayed)
- Characteristic seismic signals released
- Venting is forbidden for US and Soviet/Russian explosions by the LTBT (1974) and PNET (1974)

Nuclear Explosions in the Atmosphere or a Small Distance Underground

Types of bursts in the atmosphere —

- Air burst: fireball never touches the ground
- Surface burst: fireball touches the ground

Types of surface bursts —

- Near surface burst: $HOB > 0$, but fireball touches the ground during its expansion
- Contact surface burst: $HOB = 0$
- Subsurface burst: $HOB < 0$, but warhead explodes only a few tens of meters below ground

The amount of radioactive fallout is increased greatly if the fireball ever touches the ground.

Will the Fireball Touch the Ground?

The HOB needed to prevent the fireball from touching the ground increases much more slowly than the yield—a 6x increase in HOB compensates for a 100x increase in Y.

Examples —

- Y = 10 kt
Fireball touches ground unless HOB > 500 ft
- Y = 100 kt
Fireball touches ground unless HOB > 1200 ft
- Y = 1 Mt
Fireball touches ground unless HOB > 3000 ft

Air and Surface Bursts

Sequence of events —

- Fireball forms and rapidly expands

Example: 1 Mt explosion

Time	Diameter	Temperature
1 ms (= 10^{-3} s)	440 ft	—
10 s	5,700 ft	6,000 C

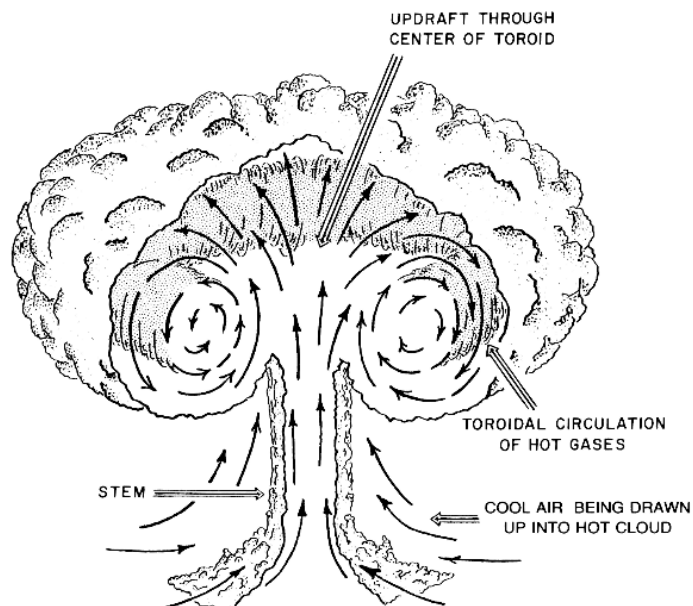
- Blast wave forms and outruns fireball
- Fireball rises and spreads, forming characteristic mushroom cloud

Final Distribution of the Energy of a Large Air Burst (Important)

The *final* distribution of the energy of a large explosion
(in order of appearance) —

- Prompt neutrino radiation ~ 5%
(not counted in the yield)
- Prompt nuclear radiation ~ 5%
- Electromagnetic pulse « 1%
- Thermal radiation ~ 35%
- Blast ~ 50%
- Residual nuclear radiation ~ 10%

Formation of the Mushroom Cloud



Formation of the Mushroom Cloud

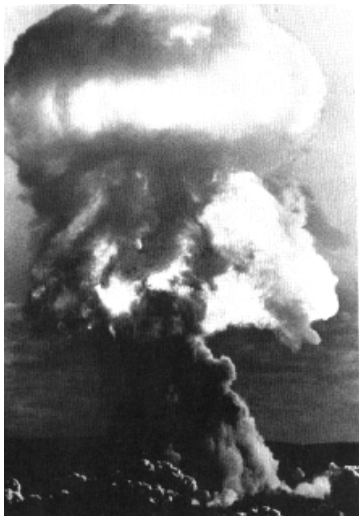


- Fireball forms and rises, sucking surrounding air inward and upward
- Moving air carries dirt and debris upward, forming stem
- Fireball rises through the unstable troposphere
- Fireball slows and spreads once it reaches the stratosphere

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Radioactivity from a Nuclear Burst



- Rock and earth is vaporized
- Highly irradiated
- Carried aloft by fireball
- Large particles “rain out”
- Small particles travel far
- Vapor condenses, falls

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Short-Term Physical Effects

Duration of key effects of a 1 Mt weapon —

- Prompt nuclear radiation (lasts $\sim 10^{-3}$ s)
 - Principally γ , β , and neutron radiation
 - Intense, but of limited range
- Electromagnetic pulse (lasts $\sim 10^{-9}$ s)
- Thermal radiation (lasts $\sim 1-10$ s)
 - X-ray and UV pulses come first
 - Heat pulse follows
- Blast (arrives after seconds, lasts < 1 s)
 - Shockwave = compression followed by high winds
 - 5 psi overpressure, 160 mph winds @ 5 mi
- Residual nuclear radiation (lasts minutes–years)
 - Principally γ and β radiation

Long-Term Physical Effects

Key long-term physical effects —

- Fallout
 - From material sucked into fireball, mixed with weapon debris, irradiated, and dispersed
 - From dispersal of material from nuclear reactor fuel rods
- Ozone depletion (Mt yields only)
 - Caused by nitrogen oxides lofted into the stratosphere
 - Could increase UV flux at the surface by $\sim 2x$ to $\sim 100x$
- Soot injected into the atmosphere cools Earth (“nuclear winter”)
 - Caused by injection of dust and soot into atmosphere
 - Scientific studies first indicated this was a big effect. Later, improved studies indicated it was probably not as important. The most recent, more sophisticated studies show these effects are important.

iClicker Question

Could a terrorist group construct a workable bomb using reactor-grade plutonium?

- A. No
- B. Yes, but with difficulty
- C. Yes, easily

Blank

iClicker Answer

Could a terrorist group construct a workable bomb using reactor-grade plutonium?

- A. No
- B. **Yes, but with difficulty**
- C. Yes, easily

iClicker Question

Nuclear Weapon Proliferation

Which of the following countries once had nuclear weapons but gave them up?

- A. Belarus
- B. Kazakhstan
- C. Ukraine
- D. South Africa
- E. All of the above

Blank

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iClicker Answer

Nuclear Weapon Proliferation

Which of the following countries once had nuclear weapons but gave them up?

- A. Belarus
- B. Kazakhstan
- C. Ukraine
- D. South Africa
- E. **All of the above**

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Nuclear Weapon Effects

Effects of Thermal Radiation

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Thermal Radiation from the Fireball

- The fireball—like any hot object—emits electromagnetic radiation over a wide range of energies
 - Initially most is at X-ray energies
 - But the atmosphere is opaque to X-rays
 - Absorption of the X-rays ionizes (and heats) the air
 - The fireball expands rapidly and then cools
 - Expansion is initially via photon diffusion, so $R \sim \text{const} \cdot t^{1/2}$
- Radiation of lower energy streams outward from surface of the fireball at the speed of light
 - Atmosphere is transparent for much of this
 - Energy cascades down to lower and lower energies
 - » Ultraviolet (UV) radiation
 - » Visible light
 - » Infrared (IR) radiation

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Effects of Thermal Radiation – 1

The seriousness of burn injuries depends on —

- The total energy released (the yield Y)
- Transparency of the atmosphere (clear or fog, etc.)
- The *slant* distance to the center of the burst
- Whether a person is indoors or out, what type of clothing one is wearing, etc.

Effects of Thermal Radiation – 2

Duration and intensity of the thermal pulse —

- 1 s for 10 kt ; 10 s for 1 Mt
- In a transparent atmosphere, the heat flux at a distant point scales as $1/D^2$ where D is the slant range
- In a real atmosphere, absorption and scattering by clouds and aerosols (dust particles) cause a steeper fall-off with D ; given by the “transmission factor” τ :

$$\tau = 60\text{--}70 \% \text{ @ } D = 5 \text{ miles on a “clear” day/night}$$

$$\tau = 5\text{--}10\% \text{ @ } D = 40 \text{ miles on a “clear” day/night}$$

- Atmosphere transmission is as complicated and as variable as the weather

Effects of Thermal Radiation – 3

Typical characteristics —

- Thermal effects are felt before the blast wave arrives
- For $Y < 10$ kt, direct effects of thermal radiation are lethal only where blast is already lethal
- For $Y > 10$ kt, direct effects of thermal radiation are lethal well beyond where blast is lethal
- Direct effects of thermal radiation are greatly reduced by shielding
- Indirect effects of thermal radiation (fires, explosions, etc.) are difficult to predict
- Interaction of thermal radiation and blast wave effects can be important

Effects of Thermal Radiation – 4

Some harmful direct effects —

- Flash blindness (temporary)
- Retinal burns (permanent)
 - Approximately 13 mi on a clear day
 - Approximately 53 mi on a clear night
- Skin burns
- Ignition of clothing, structures, surroundings

Types of burns —

- Direct (flash) burns: caused by fireball radiation
- Indirect (contact, flame, or hot gas) burns: caused by fires ignited by thermal radiation and blast

Examples of Flash Burns Suffered at Hiroshima and Nagasaki



Photo credit U.S. Department of Defense
The patient's skin is burned in a pattern corresponding to the dark portions of a kimono worn at the time of the explosion



Photo credit U.S. Air force
Burn injuries from nuclear blasts

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Thermal Radiation Units (Details)

$$Q \equiv \text{fluence} = \frac{\text{energy}}{\text{unit area}} \quad .$$

Thus

$$[Q] = \frac{\text{calories}}{\text{cm}^2} \quad .$$

Definition of calory:

1 cal = heat required to raise temperature of 1 gram of H₂O 1 C

1 cal = 4.2 Joules = 4.2 Watt-s

[Note: Dietary calories are 1000 times larger and are written with a capital "C". 1 Cal = 1,000 cal]

Example:

A 1 kilowatt (kw) hot plate emits $\frac{2}{3} \times \frac{\text{cal}}{\text{cm}^2 \times \text{sec}}$.

Thus, if you were to hold your hand right (~ 1 cm) above such a hot plate, in 10 s you would receive a fluence of

$$Q = 10 \times \frac{2}{3} = 7 \text{ cal cm}^{-2} \Rightarrow \text{2nd degree burn!}$$

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Classification of Burns

Degree	Damage to Skin	Symptoms
1st	Superficial, completely reversible; no scarring	Immediate persistent pain; affected area is red
2nd	Some skin cells survive; will heal in 2 weeks unless infection sets in	Persistent pain; scabs within 24 hours
3rd	All skin cells dead; scarring certain without skin grafts (no cells to regenerate skin)	Pain at edges of injured areas; skin looks normal, scalded, or charred

Effects of Thermal Radiation – 5

Q (cal/cm ²)	Consequences
2–6	Humans suffer 1st degree burns
5–8	Humans suffer 2nd degree burns
> 8	Humans suffer 3rd degree burns
15	Rayon fabric ignites
17	Cotton dress shirt ignites
18	Window Draperies ignite
20	Blue jeans ignite
30	Asphalt roofing ignites

Conflagrations Versus Firestorms

Conflagration —

- Fire spreads outward from the ignition point(s)
- Fire dies out where fuel has been consumed
- The result is an outward-moving ring of fire surrounding a burned-out region

Firestorm —

- Occurs when fires are started over a sizable area and fuel is plentiful in and surrounding the area
- The central fire becomes very intense, creating a strong updraft; air at ground level rushes inward
- The in-rushing air generates hurricane-force winds that suck fuel and people into the burning region
- Temperatures at ground level exceed the boiling point of water, people are baked and asphyxiated

Physics 280: Session 10

Plan for This Session

Student questions, news, and discussion

iClicker questions soon and later in the class

Module 3: Effects of nuclear explosions (cont'd)

Tuesday: CBS Documentary “Ground Zero”

Session 10: News and Discussion

Global Security Newswire

by National Journal Group

Daily news on nuclear, bio
chemical weapons, terr
related issues.

Russia Sees Threat to Pakistani Nukes

Tuesday, Feb. 16, 2010

A top Russian national security body has warned that militants could acquire nuclear weapons from Pakistan's arsenal, either by force or through a position of authority, Interfax reported yesterday (see **GSN**, Feb. 12).

"We see that as a big potential threat," said Russian Security Council Deputy Secretary Vladimir Nazarov. "We need to be serious about this threat," he said.

Session 10: News and Discussion

Iranian Nuclear Program Could Spark Major Regional Arms Race, Nunn Says

Wednesday, Feb. 17, 2010

Former U.S. Senator Sam Nunn (D-Ga.) said that Iran's nuclear efforts could lead to a major atomic arms race in the Middle East, the *Atlanta Journal-Constitution* reported Monday (see **GSN**, Feb. 12).

"The governments of the world must understand what a threat it is if the Iranians get nuclear weapons because there are probably 10 other countries in the Middle East over the next 10 to 20 years that would follow down the road," he said.

Session 10: News and Discussion

Obama Signs Nuclear Forensics Bill

Wednesday, Feb. 17, 2010

U.S. President Barack Obama yesterday signed legislation intended to bolster U.S. technical expertise in the field of nuclear forensics and attribution as part of national efforts to deter acts of nuclear terrorism (see **GSN**, Dec. 24, 2009).

The **Nuclear Forensics and Attribution Act** mandates the establishment of the National Technical Nuclear Forensics Center within the Homeland Security Department. It also requires the department to create a program that would provide academic funding to undergraduate and graduate students interested in pursuing a career in the field, according to the White House (White House **release**, Feb. 16).

iClicker Question

What are the three stages of a large thermonuclear bomb?

- A. fission-fission-fission
- B. fission-fission-fusion
- C. fission-fusion-fission
- D. fusion-fission-fusion
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Blank

iClicker Answer

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- C. fission-fusion-fission**
- D. fusion-fission-fusion
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iClicker Question

What is the fundamental limit on the yield of a thermonuclear bomb?

- A. 1 kt
- B. 100 kt
- C. 1 Mt
- D. 100 Mt
- E. There is no limit

Blank

iClicker Answer

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iClicker Question

Which of the following effects of a Megaton explosion would be felt **first** 5 miles away?

- A. Blast
- B. Prompt nuclear radiation
- C. Thermal radiation
- D. Electromagnetic pulse
- E. Residual nuclear radiation (“fallout”)

Blank

iClicker Answer

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- D. Electromagnetic pulse
- E. Residual nuclear radiation (“fallout”)

iClicker Question

Which of the following effects of a Megaton explosion would be felt **last** 5 miles away?

- A. Blast
- B. Prompt nuclear radiation
- C. Thermal radiation
- D. Electromagnetic pulse
- E. Residual nuclear radiation (“fallout”)

Blank

iClicker Answer

Which of the following effects of a Megaton explosion would be felt **last** 5 miles away?

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- C. Thermal radiation
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- E. **Residual nuclear radiation (“fallout”)**

iClicker Question

Nuclear Weapon Effects

Which effect listed below carries the largest fraction of the total energy of a Megaton nuclear explosion?

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Blank

iClicker Answer

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Effects of Nuclear Explosions

Effects of Blast Waves

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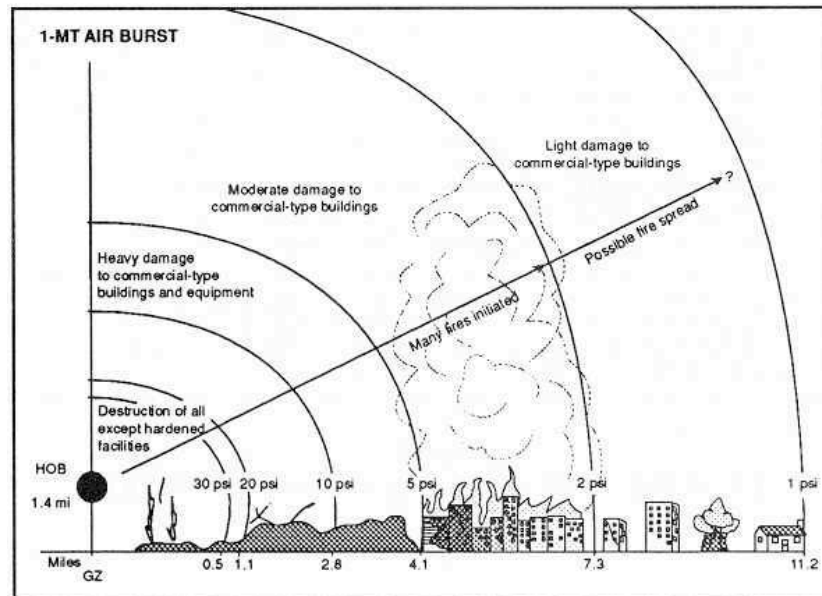
Blast Wave Pressures and Winds

Pressure (psi)	Dynamic Pressure (psi)	Wind (mph)
200	330	2,078
150	222	1,777
100	123	1,415
50	41	934
20	8	502
10	2	294
5	1	163

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Damaging Effects of a Blast Wave



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Damaging Effects of a Blast Wave

- The blast wave is considered the most militarily significant effect of a nuclear explosion in the atmosphere
- Because its peak pressure P is proportional to Y/D^3 , the distance at which P (and hence the damage) is of a given size is proportional to $Y^{1/3}$; this is called "cube-root" scaling
- Like any shockwave, a blast wave produces —
 - A sudden isotropic (same in all directions) pressure P that compresses structures and victims

This is followed by

- A strong outward wind that produces dynamic pressure Q that blows structures and victims outward
- The two pressures are directly related; both are usually given in psi = pounds per square inch

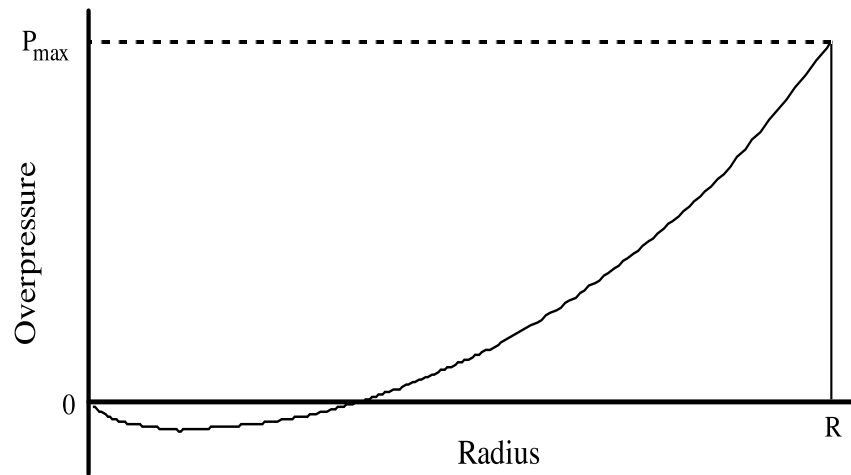
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Shape of a Blast Wave

A snapshot in time: Pressure vs. Radius

Shock Wave Pressure Distribution



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Effects of Thermal Radiation and Blast on Houses



Effect of a 16 kt explosion on a house 1 mi away
(equivalent to a 1 Mt explosion on a house 5 mi away, but happens 10x faster)

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Effects of Shallow Underground Nuclear Explosions

Example: The Sedan Test (100 kt, 1962)



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Effects of Shallow Underground Nuclear Explosions

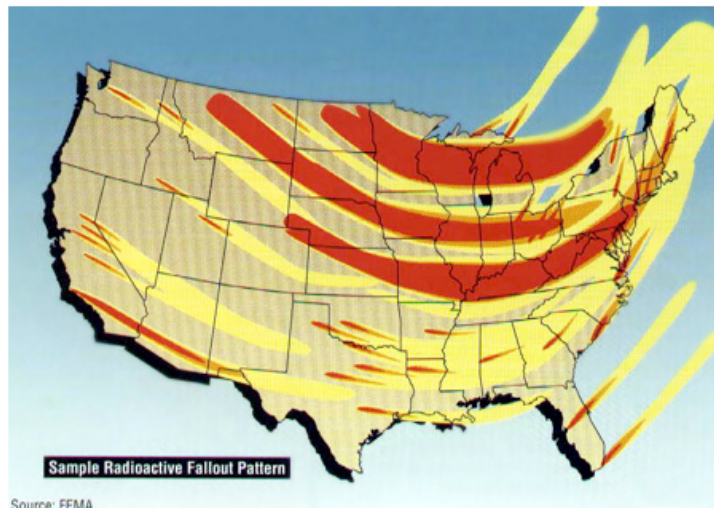
Effects of the Sedan Event (1962)

- Explosive yield: 100 kt
- Depth of burial: 635 feet
- Crater radius: 610 feet
- Crater depth: 320 feet
- Earth displaced: 12 million tons

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Effects of Nuclear Explosions



Source: FEMA

Map of nuclear fallout distribution after a potential nuclear attack on the United States. Source: FEMA

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Nuclear Explosions in Air Produce a Characteristic “Double Flash” of Light

- The strong shockwave produced by a nuclear explosion heats the air through which it passes, making it opaque
- Consequently, once the shockwave is outside the fireball, an observer can see only the gas heated by the shockwave, which is cooler than the gas in the fireball
- As the shockwave expands it weakens, its brightness drops, and the explosion dims, ending the first flash
- A short while later the shockwave becomes so weak that it no longer makes the air through which it passes opaque
- At this point the much hotter fireball becomes visible again and the explosion brightens temporarily before fading as the fireball expands and cools
- This sequence of events produces the characteristic “double flash” of light of a nuclear explosion in the atmosphere, which sensors on satellites orbiting Earth can use to detect and identify air and surface bursts

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Effects of Nuclear Explosions

Effects of Nuclear Radiation

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Non-Nuclear and Nuclear Radiation

Non-nuclear electromagnetic radiation —

- Radio frequency (RF) radiation
- Optical radiation: UV, VIS, IR (atomic and molecular transitions)
- X-rays (from electronic transitions in atoms)

Nuclear radiation —

- Alpha radiation: α (nuclear decay)
- Beta radiation: β^\pm (nuclear decay)
- Gamma radiation: γ (nuclear de-excitation)
- Neutrons: n (fission & fusion)
- Fission fragments and other heavy ions

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Categories of Nuclear Radiation

Categories of radiation based on **the source** —

- *Prompt nuclear radiation* from fission reactions in the weapon and from radioactive decay of fission fragments (~ 5% of Y)
- *Delayed nuclear radiation* from the radioactivity of the material in the weapon (e.g., the case) or later engulfed in the fireball (~ 5%–10% of Y)

Categories of radiation based on **when it is absorbed** —

- *Initial radiation* (during the first minute): n, γ
- *Residual radiation* (after the first minute): n, γ , some β ; α -radiation over very long times, if ingested

Effects of Radiation on Matter – 1

Two distinct types of radiation (*very important*) —

- Non-ionizing radiation: RF, optical (IR, VIS, UV)
- Ionizing radiation: α , β , γ , n, fission fragments, heavy ions, most X-rays

These two types have different effects on matter —

- Non-ionizing radiation causes heating
 - Very well understood
 - Can damage biological systems if the temperature becomes too high
- Ionizing radiation breaks chemical bonds
 - Generally well understood
 - Long-term effects of very low level exposures are controversial, primarily because experiments and epidemiology are so difficult for this case

Effects of Radiation on Matter – 2

Important to distinguish two classes of materials —

- Inert matter
- Living matter (biological organisms)

Different measures are used to quantify —

- Physical exposure
- Biological exposure

Biological organisms have received the most attention (especially humans) —

- Ionizing radiation is the main concern
- Animals are more vulnerable than plants
- Higher animals are more vulnerable than (some) lower animals

Physical Effects of Ionizing Radiation – 1

Physical causes of biological effects—

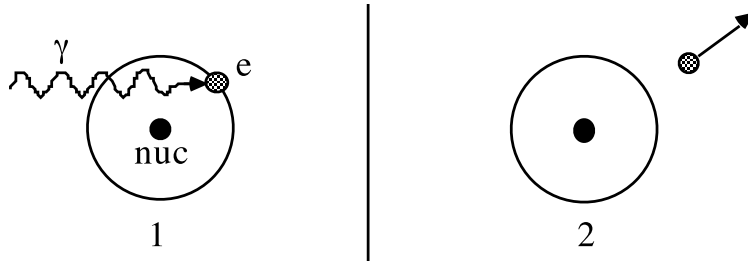
- Radiation strips electrons from atoms and molecules (this process is called “ionization”)
- Ionization changes the chemical properties of the atoms and molecules
- The changes in chemical properties can cause damage to biological molecules, cells, and tissues
- This damage may cause malfunction or death

Two modes of ionization—

- Direct ionization (charged particles and photons)
- Indirect ionization (neutrons)

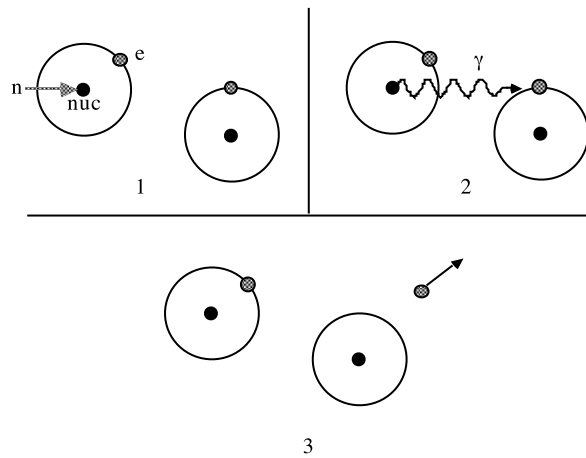
Physical Effects of Ionizing Radiation – 2

Direct Ionization



Physical Effects of Ionizing Radiation – 3

Indirect Ionization



Physical Effects of Ionizing Radiation – 4

With a few exceptions, nuclear radiation does *not* make the irradiated object radioactive —

- Neutron activation (activation by irradiation with neutrons)
 - Adding neutrons can turn a stable isotope into a radioactive one that emits γ -rays or β -rays
 - Measuring precisely the energy of photon (or electron) that is emitted can uniquely identify the chemical species
 - used as standard laboratory and field diagnostic
- Irradiation by highly energetic photons (γ -rays) or electrons (β -rays) can also make stable nuclei radioactive

Irradiation of foods to kill harmful bacteria —

- Has been approved by the U.S. Department of Agriculture (DOA) and the Food and Drug Administration (FDA)
- Accepted by the public remains to be determined

The Bad News

A non-functional protein might be produced —

- Cell repair mechanisms may be affected
- Immunological pathways may be shutdown
- Cellular metabolism may be affected greatly

A protein with a different function might be produced —

- An enzyme that helps break down estro-diols (estrogen products) can easily be modified at the genetic level to convert testosterone to estrogen! (Most beers have this enzyme to begin with. Beer gut and saggy man-breasts, anyone?)

Damage caused by a large dose of radiation cannot be repaired —

- Radiation sickness is a good example
- Mammals exposed to lethal doses of radiation simply decay, their organ systems shutting down one by one

The Good News

Mutations like these happen all the time and are not a serious problem

The human genome is so large that most mutations occur in non-coding regions that contain only “junk”

If a single cell acquires a mutation it does not mean that every cell in the organism will misbehave —

- Cells produce minute amounts of enzymes, etc. Usually many, many cells must suffer the same mutation before the organism is seriously affected.

Cells have mechanisms for checking DNA damage —

- If a cell cannot repair the damage, it often enters a self-regulated death cycle (apoptosis), preventing itself from passing on the mutation(s) to its progeny.
- However, mutations sometimes interfere with this process, and the cell does pass on its bad attributes (cancer).
- Radiation sickness and burns are partially caused by cells that kill themselves.

Effects of Radiation (Review)

Ionizing radiation is the main concern —

- Breaks chemical bonds
- Can damage inert material
- Can damage biological systems
 - Short-term (“acute”) exposure: ~ 1 day or less
 - Long-term (“chronic”) exposure: days to years
- Mostly well-understood
 - Exception: long- term effects of low levels of exposure received over long periods
 - Example: cancer rates 20 to 40 years later

Non-ionizing radiation causes heating —

- If it produces a high temperature, harm can occur
- Well understood

Physics 280: Session 11

Plan for This Session

Video: CBS Documentary “Ground Zero”

iClicker questions later in the class

Module 3: Effects of nuclear explosions (cont'd)

New readings on terrorism and insurgencies

Notes on the “Ground Zero” Video

A 1982 CBS News Documentary

- US and SU were “weapon rich” (US: >12,000 NWs; SU: > 8,000 NWs)
- Stimulation of fears was similar to today, but much more intense
- Soviet capabilities were greatly *overstated*, U.S. capabilities were *understated*, the likely effects of nuclear war were being enormously *understated*
 - Reagan administration: “with enough shovels, we will all survive”
 - Briefing by White House Director of Emergency Communications
- Some 4,000 large strategic nuclear weapons are still on high alert

The consequences of a terrorist attack would be different from the consequences of a large nuclear attack; protective measures could be more effective

“Ground Zero” also provides an introduction to
Module 5: Delivery of Nuclear Weapons

Physics 280: Session 12

Plan for This Session

Student questions, news, and discussion
iClicker questions soon and later in the class
Module 3: Effects of nuclear explosions (cont'd)
Module 4: Nuclear Terrorism
New readings on terrorism and insurgencies

Session 12: News and Discussion

The CHRISTIAN SCIENCE
MONITOR

Horizons

Airborne laser shoots down missile in mid-flight

By Chris Gaylord

posted February 12, 2010 at 3:58 pm EST

Last night, the military officially entered the age of airborne laser weapons. A large laser mounted to the front of a modified 747 jet successfully detected and shot down a ballistic missile while both were in mid-flight.

Session 12: News and Discussion

Axis of Logic

Finding Clarity in the 21st Century Mediaplex

World News

Romania's decision to host US missiles sparks regional domino effect

By Robert Bridge

Russia Today

Saturday, Feb 20, 2010

Romania and Moldova have kicked off bilateral talks as unrecognized republic Transdniester says it's ready to host Russian missiles on its soil. Meanwhile, Bulgaria is considering its participation in US missile defense.

Session 12: News and Discussion

Global Security Newswire

by National Journal Group

Daily news on nuclear, biological and chemical weapons, terrorism and related issues.

Leaders See Pressing Need to Complete Nuke Pact, Official Says

Thursday, Feb. 25, 2010

U.S. President Barack Obama and Russian President Dmitry Medvedev agreed in a telephone conversation yesterday that they must push their negotiating teams to finish work on a major nuclear arms control agreement, a White House official told the Associated Press (see **GSN**, Feb. 24).

iClicker Question

What is the fundamental limit on the yield of a thermonuclear bomb?

- A. 1 kt
- B. 100 kt
- C. 1 Mt
- D. 100 Mt
- E. There is no limit

Blank

iClicker Answer

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iClicker Question

Which of the following effects of a Megaton explosion would be felt **first** 5 miles away?

- A. Blast
- B. Prompt nuclear radiation
- C. Thermal radiation
- D. Electromagnetic pulse
- E. Residual nuclear radiation (“fallout”)

Blank

iClicker Answer

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- C. Thermal radiation
- D. Electromagnetic pulse
- E. Residual nuclear radiation (“fallout”)

iClicker Question

Which of the following effects of a Megaton explosion would be felt **last** 5 miles away?

- A. Blast
- B. Prompt nuclear radiation
- C. Thermal radiation
- D. Electromagnetic pulse
- E. Residual nuclear radiation (“fallout”)

Blank

iClicker Answer

Which of the following effects of a Megaton explosion would be felt **last** 5 miles away?

- A. Blast
- B. Prompt nuclear radiation
- C. Thermal radiation
- D. Electromagnetic pulse
- E. **Residual nuclear radiation (“fallout”)**

iClicker Question

Nuclear Weapon Effects

Which effect listed below carries the largest fraction of the total energy of a Megaton nuclear explosion?

- A. Prompt nuclear radiation
- B. Electromagnetic pulse
- C. Thermal radiation
- D. Blast
- E. Residual nuclear radiation (“fallout”)

Blank

iClicker Answer

Nuclear Weapon Effects

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Ionizing radiation is the main concern —

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- Mostly well-understood
 - Exception: long- term effects of low levels of exposure received over long periods
 - Example: cancer rates 20 to 40 years later

Non-ionizing radiation causes heating —

- If it produces a high temperature, harm can occur
- Well understood

Effects of Ionizing Radiation

It's important to distinguish —

- Source activity = rate of particle emission
(e.g., the number of particles emitted per second)
- Physical *dose-rate* (rate at which energy is absorbed)
- Physical *dose* (total energy absorbed; an integrated measure)
- Biological *dose-rate* (describes rate at which living tissue is affected)
- Biological *dose* (describes total consequences to living tissue; an integrated measure)
- *No unit has yet been defined to characterize genetic damage*

Effects of Ionizing Radiation

Measuring *source activity* —

- Geiger Counters measure activity
= number of nuclear decays per second
- Traditional unit: curie (Ci)
 - Definition: 1 Ci = 3.7×10^{10} decays per sec
 - Activity of 1 g of radium is 1 Ci
- Modern (SI) unit : becquerel (Bq)
 - Definition: 1 Bq = 1 decay per sec
- Examples of radioactive sources
 - Co-80 sources used in medicine: 100-1,000 Ci
 - Spent fuel from a 1 GW nuclear reactor: 5×10^9 Ci (initially)
 - 1 Mt nuclear weapon: 10^{11} Ci (prompt radiation)
- The activity of a source tells you *nothing* about the physical or biological consequences!

Effects of Ionizing Radiation

Physical effects —

- Characterized by the *physical* dose or exposure
= total energy absorbed
- Measured by devices (such as film badges) that record the *cumulative* exposure
- The physical dose measures the overall effect of ionizing radiation on *inert* matter
- Traditional unit: rad (1 rad = 10^{-5} J/g)
- Modern (SI) unit: gray (1 Gy = 10^{-3} J/g = 100 rad)

Effects of Ionizing Radiation

Biological effects —

- Characterized by the biological dose (or dose-equivalent)
- The biological dose is a good overall measure of the magnitude of the biological effect of interest
- The biological effect of a physical dose depends on
 - The type and energy of the radiation
 - The type of biological tissue (skin, cornea, etc.)
 - The type of damage of interest

Effects of Ionizing Radiation

Quality factor —

- The *quality factor* describes how much damage a given type of radiation causes; it depends on the *radiation*, the *tissue*, and the *type of damage*
- Traditional unit: rem (“roentgen equivalent mammal”) (1 rem = quality factor x 1 rad)
- Modern (SI) unit: sievert (Sv) (1 sievert = quality factor x 1 gray)
- Rough conversion factor: 1 Sv = 100 rem

Examples of Exposures – 1

Dose rates due to natural background —

- 2 to 3 mSv/yr is a representative number ($1 \text{ mSv} = 10^{-3} \text{ Sv}$)
 - Quoted natural background exposure rates have varied from 10^{-5} Sv/yr , up to 1 mSv/yr, but both are out of date!
 - The estimated natural background exposure rate more than doubled when radon was discovered in buildings!

Maximum permissible dose rates (now?) —

- Max dose rate for workers in industry and medicine: 5.0 rem/yr (no more than 25 rem over a lifetime is allowed)
- Population must be protected if dose exceeds 25 rem
- Population must be evacuated if dose exceeds 75 rem

Examples of Exposures – 2

Examples of medical exposures —

- Modern chest X-ray = 20 mrem
- Heart X-ray (angiogram) $\approx 2 \text{ rem/image}$
- Cat scan $\approx 100 \text{ rem} \sim 1 \text{ Sv per image}$

LD₅₀ biological dose (Lethal Dose-50: healthy young adults have a 50% probability of survival with good medical attention) —

- LD₅₀ = 450 rem = 4.50 Sv (acute exposure, whole body)

Very high doses —

- 10,000 rem: immediate neurological impairment
- 3,000 rem; death in hours
- 1,000 rem: death in days
- 450 rem: 50% chance of survival
- 300 rem: severe radiation sickness

Fallout Radiation from a 1 Mt Burst

Assume —

- Surface burst
- Wind speed of 15 mph
- Time period of 7 days

Distances and doses —

- 30 miles: 3,000 rem (death within hours; more than 10 years before habitable)
- 90 miles 900 rem (death in 2 to 14 days)
- 160 miles: 300 rem (severe radiation sickness)
- 250 miles: 90 rem (significantly increased cancer risk; 2 to 3 years before habitable)

iClicker Question

Nuclear Weapon Proliferation

Which of the following countries once had nuclear weapons but gave them up?

- A. Belarus
- B. Kazakhstan
- C. Ukraine
- D. South Africa
- E. All of the above

Blank

iClicker Answer

Nuclear Weapon Proliferation

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- A. Belarus
- B. Kazakhstan
- C. Ukraine
- D. South Africa
- E. **All of the above**

iClicker Question

Which of the following is **not** a provision of the Nuclear Nonproliferation Treaty?

- A. Nuclear weapons states must give up all their nuclear weapons.
- B. Non-nuclear weapon states are guaranteed the right to enrich uranium and produce plutonium.
- C. Non-nuclear weapon states must not accept or manufacture nuclear weapons.
- D. Nuclear weapons states must not give nuclear weapons to non-nuclear weapon states or help them develop weapons.
- E. All of the above are provisions of the treaty.

Blank

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- D. Nuclear weapons states must not give nuclear weapons to non-nuclear weapon states or help them develop weapons.
- E. **All of the above are provisions of the treaty.**

Nuclear Explosions

Possible Effects of Nuclear War

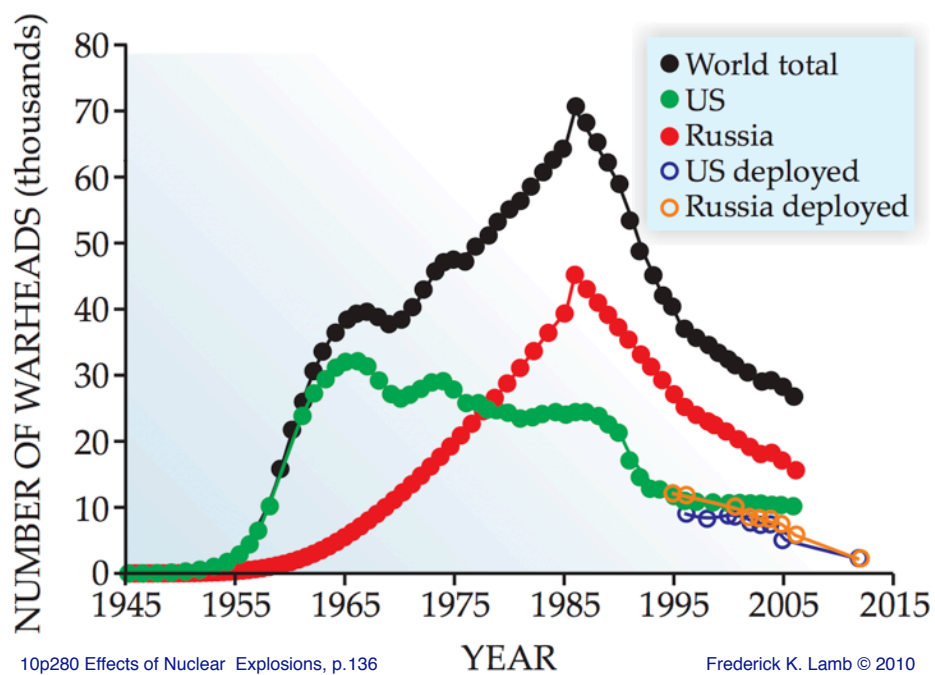
Possible Effects of Nuclear War

Read and Study *The Day After Midnight*

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Effects of Nuclear War



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Effects of Nuclear War

Illustrative Effects

1,000 weapons detonated on U.S. industrial targets would *immediately* —

- kill 20% of the total population
- injure an additional 16% of the total population

A regional war between India and Pakistan could generate 5 Tg of soot, sufficient to —

- produce the lowest temperatures for 1,000 years, lower than the Little Ice Age or 1816 (“the year without a summer”)
- reduce precipitation in the Asian monsoon region by 40%
- substantially reduce the length of the growing season in the U.S. midwest

Mean time for soot to decrease is 5 years

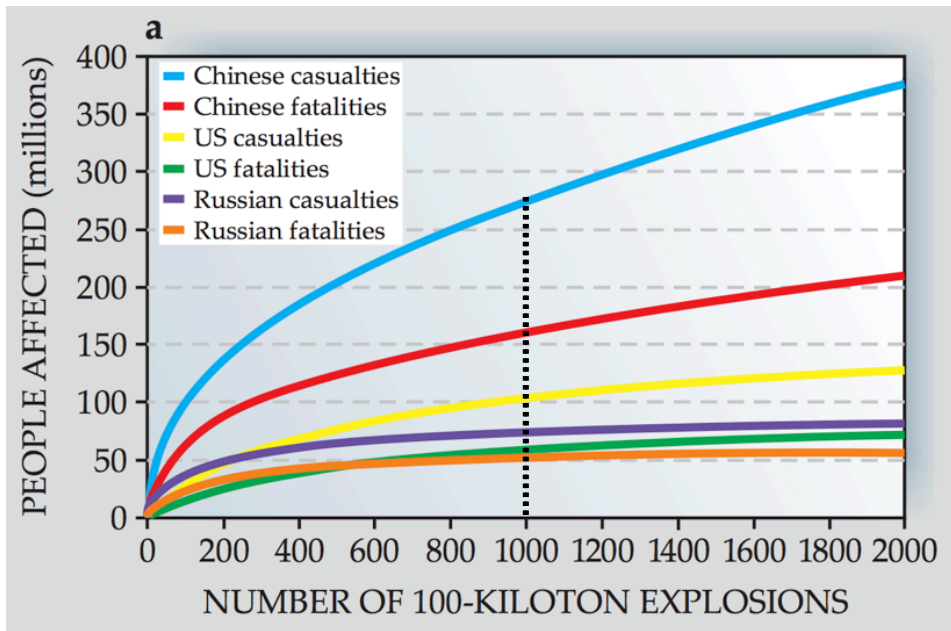
Effects of Nuclear War

Conclusions

Just 1,000 weapons detonated on the U.S. would immediately kill or injure 100 million people (~ 35% of the total population)

Just 1,000 weapons detonated on the Russia would immediately kill or injure 70 million people (~ 50% of the total population)

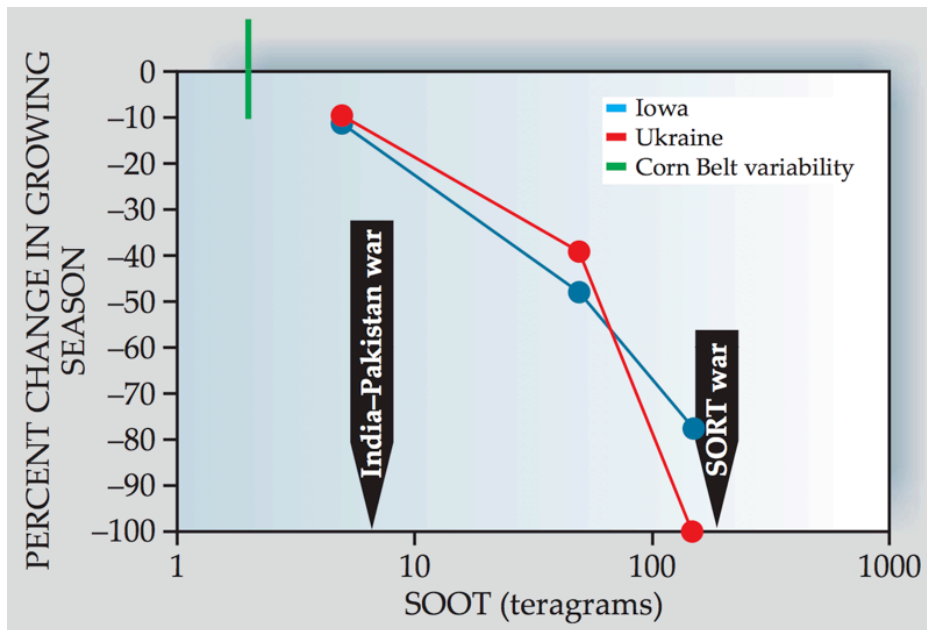
Effects of Nuclear War



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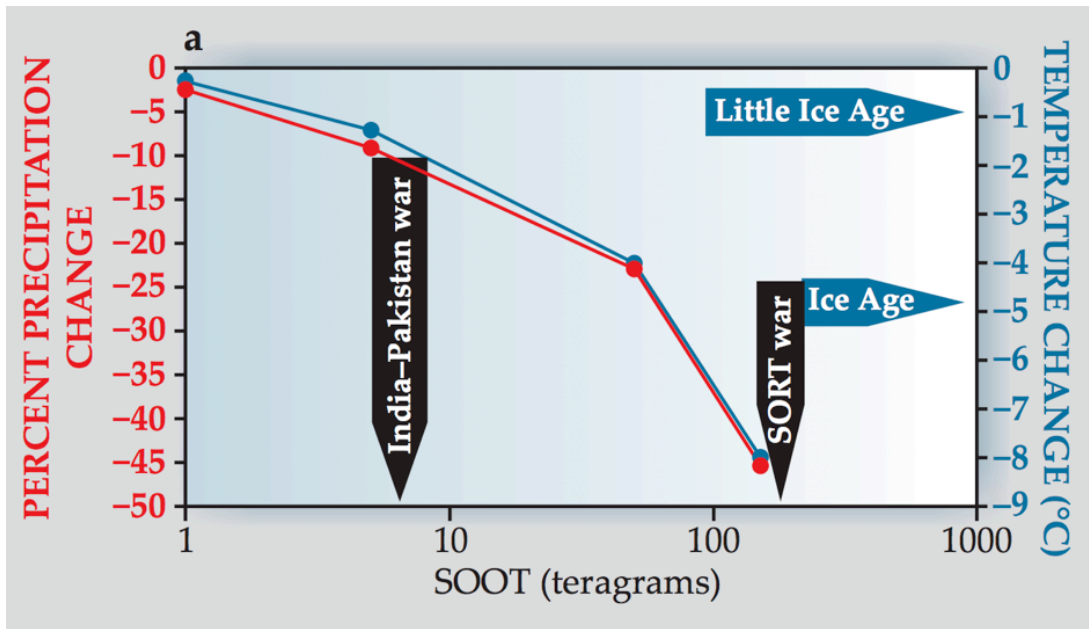
Effects of Nuclear War



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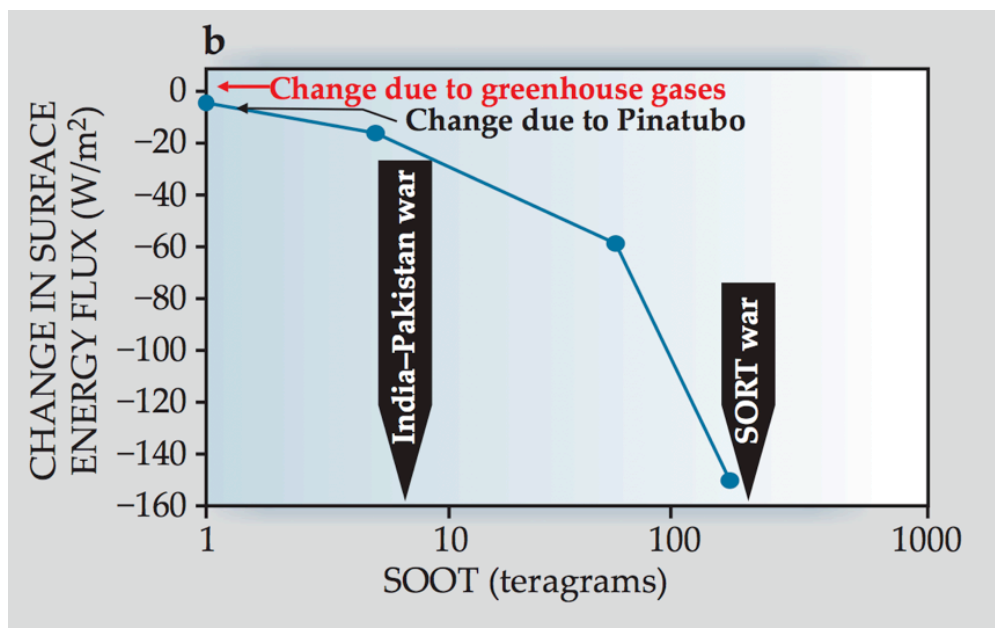
Effects of Nuclear War



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Effects of Nuclear War



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Effects of Nuclear War

Indirect Effects Would Be the Most Important

“What can be said with assurance...is that the Earth’s human population has a much greater vulnerability to the indirect effects of nuclear war, including damage to the world’s —

- agricultural
- transportation
- energy
- medical
- political
- and social

infrastructure than to the direct effects of nuclear war.”

End of Basic Slides

Supplementary Slides

Creation of the Blast Wave (Details)

- The pressure of the super-hot gas in the fireball is a million times greater than that of the surrounding air, so the fireball expands rapidly outward (the diameter of the fireball produced by a 1 Mt explosion is more than a mile across a few seconds after the explosion starts)
- The “bubble” of super-hot gas expands rapidly, pushing violently outward on the surrounding air and generating a very strong outward-moving shockwave
- Initially X-rays from the fireball rapidly penetrate and heat the surrounding air, causing the fireball to expand faster than either the gas inside or the shockwave
- The fireball expands more slowly with time and the rapidly expanding shockwave catches up and passes through fireball's surface; this is called “breakaway”
- From this moment onward the shockwave gets little push from the fireball; it propagates outward on its own

Properties of a Blast Wave (Details)

- A “blast wave” is a very strong shockwave called that moves outward at supersonic speeds; the larger the yield of the nuclear weapon, the faster it moves
- The mathematics of a blast wave are very elegant; the solution is often called “the Sedov-Taylor solution”
- This solution depends only on —
 - the yield Y of the explosion
(all other aspects of the source quickly forgotten)
 - the density and pressure law of the surrounding air
- A blast wave is “self-similar”
 - Its shape is the same for any yield and any radius
 - The peak pressure fixes all other parameters
- The peak pressure P is proportional to Y/D^3
 - Consequently the distance at which P is of a given size is proportional to $Y^{1/3}$; this is called “cube-root” scaling

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Energy From a Single Fission



Energy Distribution (MeV)	
Kinetic energy of fission fragments	~ 165*
Energy of prompt gamma-rays	7*
KE of prompt neutrons	5
KE of beta-rays from fragments	7
E of gamma-rays from fragments	6
E of neutrinos from fragments	10
Total	~ 200

*Only this 172 MeV is counted in the explosive “yield” of nuclear weapons

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Self-Similarity of Blast Waves

This is supplementary information for those who are interested

Self-Similarity of Blast Waves

At early times following detachment from the fireball, the blast wave is *strong* and *self-similar*.

A wave is self-similar if the *shape* of the variation with radius of all physical quantities (such as the pressure, wind speed, etc.) *remains the same as the shockwave expands*.

It is because the shockwave is initially strong that it *becomes* self-similar —

- A strong shockwave that is *not initially* self-similar will *become* self-similar as it expands
- A strong shockwave that has *become* self-similar will *remain* self-similar as it expands, until cooling occurs

Properties of a Blast Wave

- A “blast wave” is a very strong shockwave called that moves outward at supersonic speeds; the larger the yield of the nuclear weapon, the faster it moves

Self-Similarity of Blast Waves

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Prompt Nuclear Radiation

Sources —

- n 's and γ 's produced during fission and fusion of the nuclear fuel in the weapon
- delayed n 's from nuclear material in the weapon
- γ 's from (n,γ) -reactions of n 's with weapon case and/or matter in the nearby environment

Characteristics —

- Mean free paths in air of ~ 20 – 200 m
- Mean free paths in tissue of ~ 20 cm
- Very effective in damaging living things

Range of Radiation and Blast

Range in meters of radiation and blast effects

Weapon	Radiation Dose (rads)			Overpressure (psi)		
	8,000	3,000	650	17	6	3
1-kt fission	360	440	690	300	520	910
10-kt fission	690	820	1100	640	910	1520
1-kt ERW	690	820	1100	280	430	760

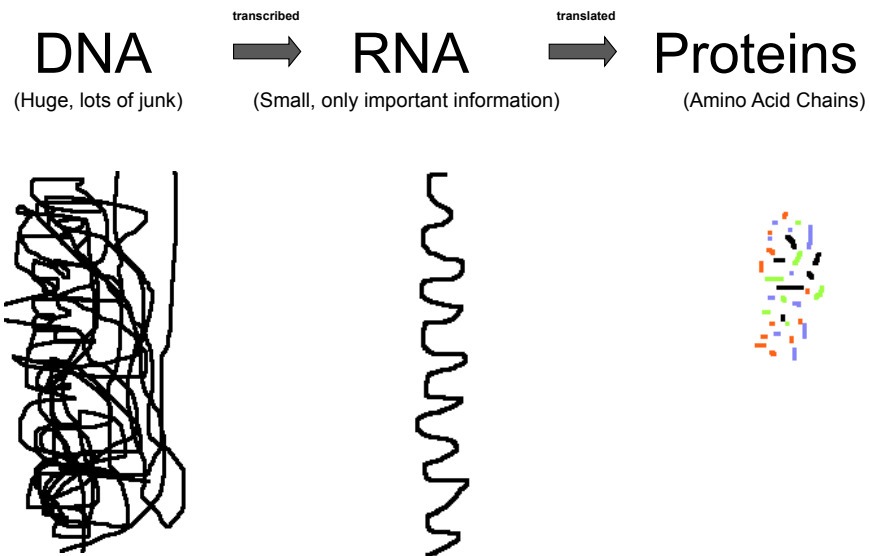
Genetic Effects of Ionizing Radiation

Radiation-Induced Mutations

...how one little error *could* mess things up

— Courtesy of Richard L. Styles
and Matthew K. Fischer

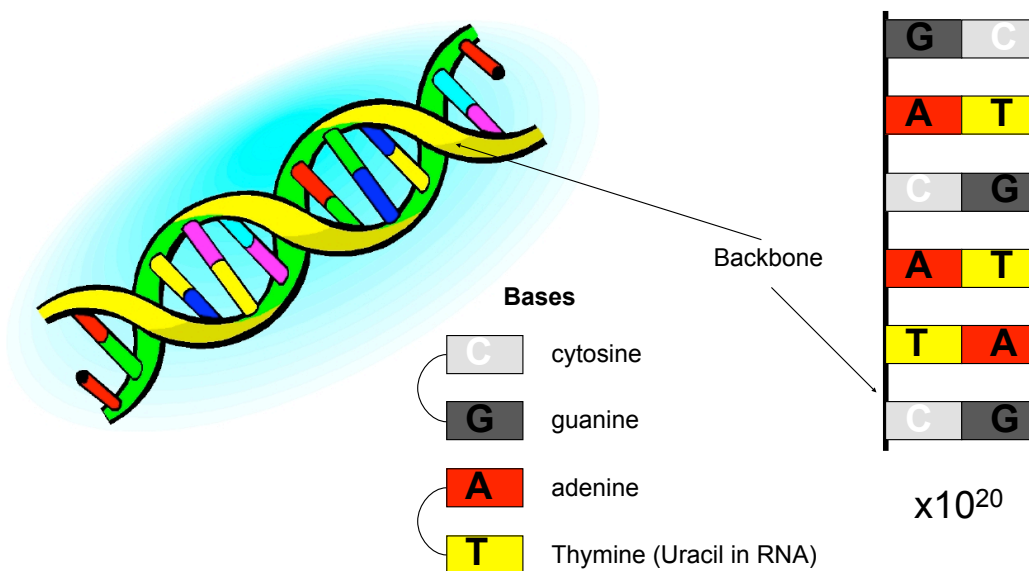
The Central Dogma of Molecular Biology



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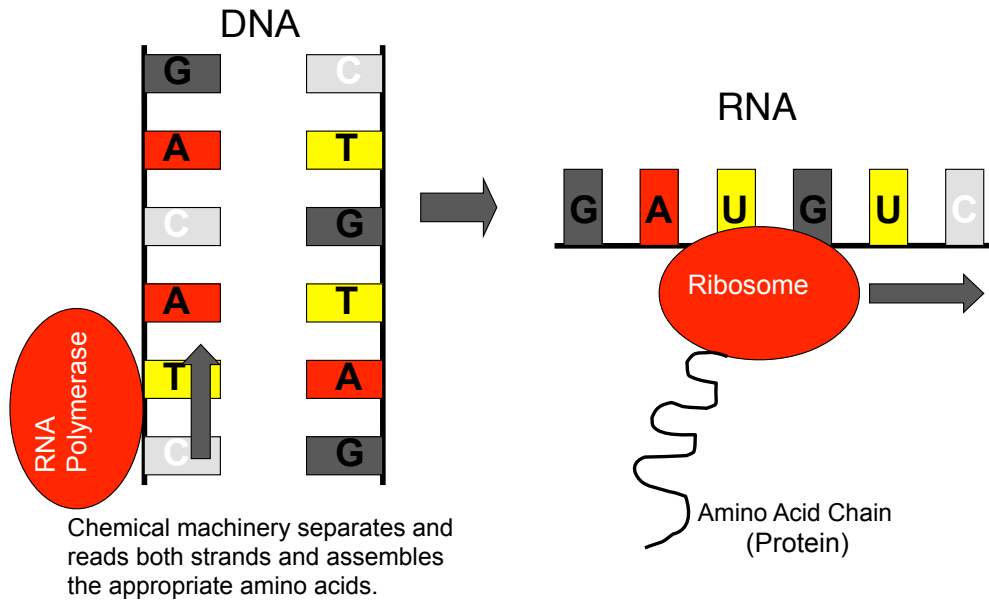
DNA – Up Close and Personal



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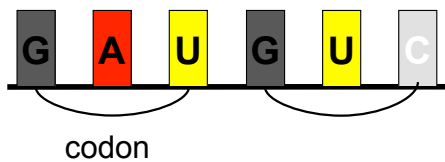
Translating the Information



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The Code



Every 3 bases make up a codon.

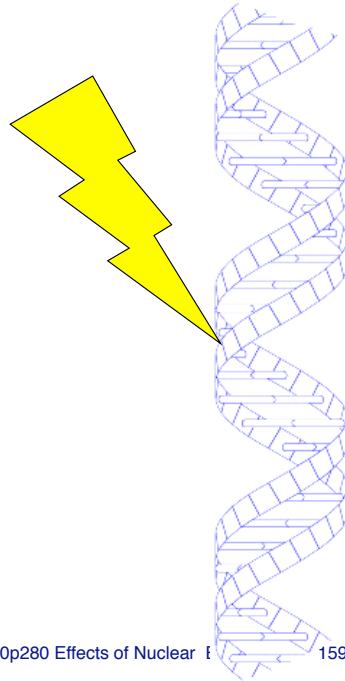
Codons tell the chemical machinery which of the 20 amino acids to recruit and add to the chain.

FIRST	SECOND			THIRD	
-	U	C	A	G	-
U	Phe Phe Leu Leu	Ser Ser Ser Ser	Tyr Tyr Stop Stop	Cys Cys Stop Trp	U C A G
C	Leu Leu Leu Leu	Pro Pro Pro Pro	His His Gln Gln	Arg Arg Arg Arg	U C A G
A	Ile Ile Ile Met	Thr Thr Thr Thr	Asn Asn Lys Lys	Ser Ser Arg Arg	U C A G
G	Val Val Val Val/Met	Ala Ala Ala Ala	Asp Asp Glu Glu	Gly Gly Gly Gly	U C A G

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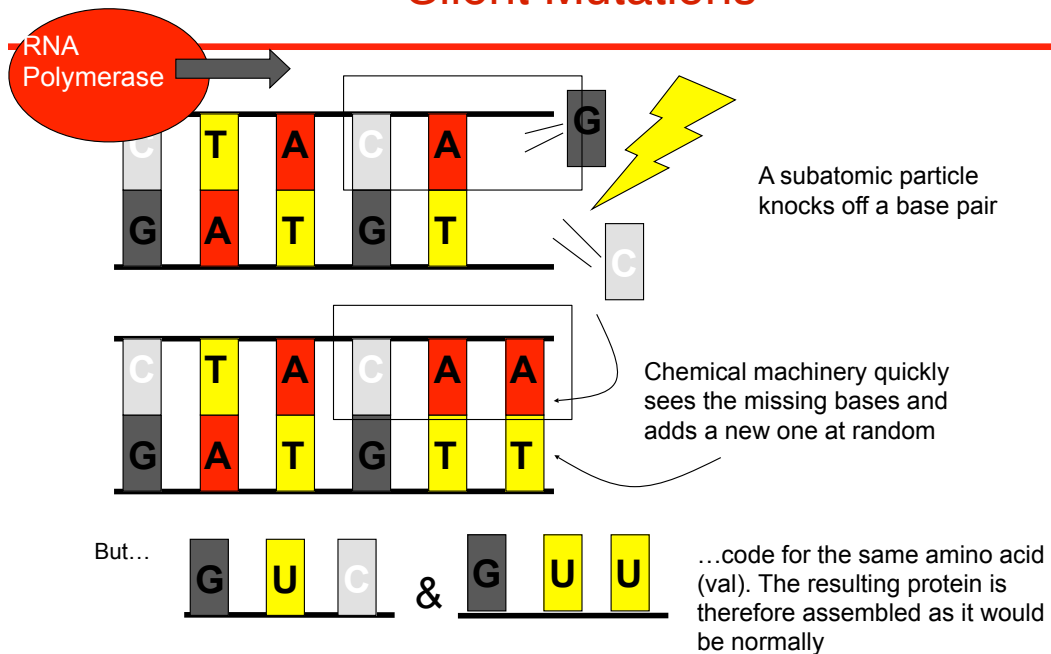
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Radiation-Induced Mutations

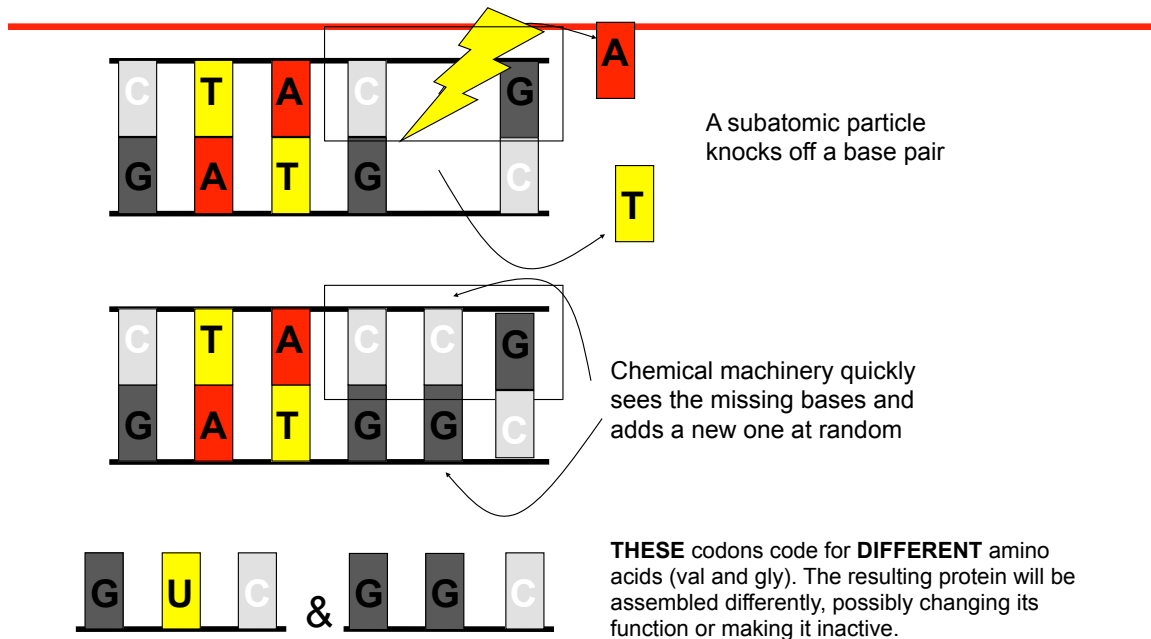


- Silent
- Missense
- Nonsense
- Frame-shift
- Deletion

Silent Mutations



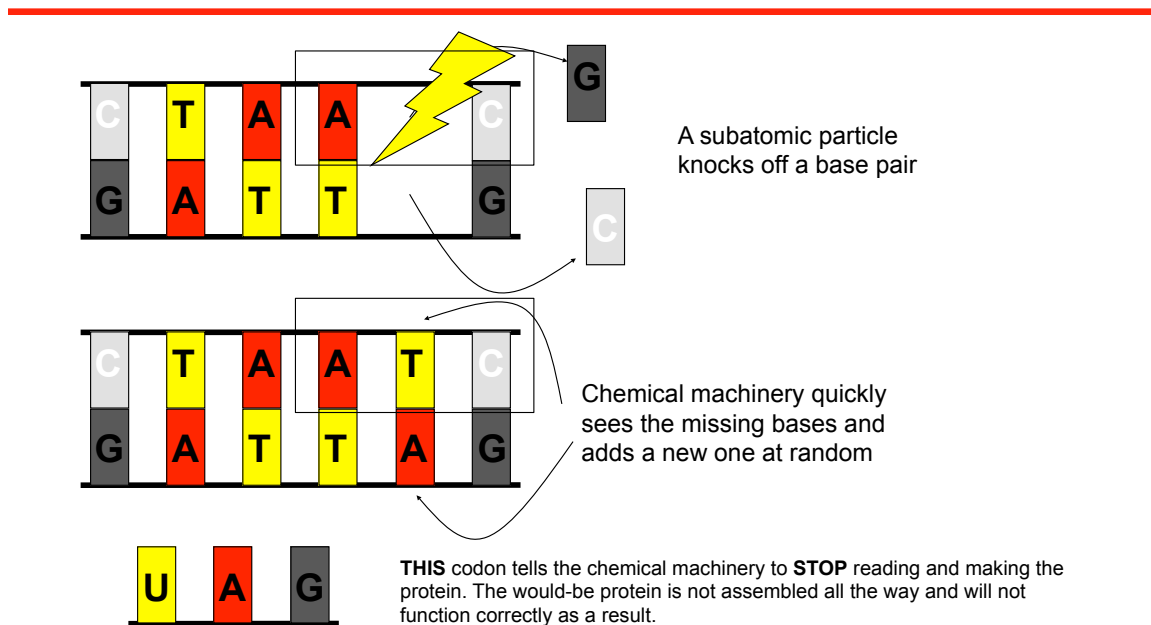
Missense Mutations



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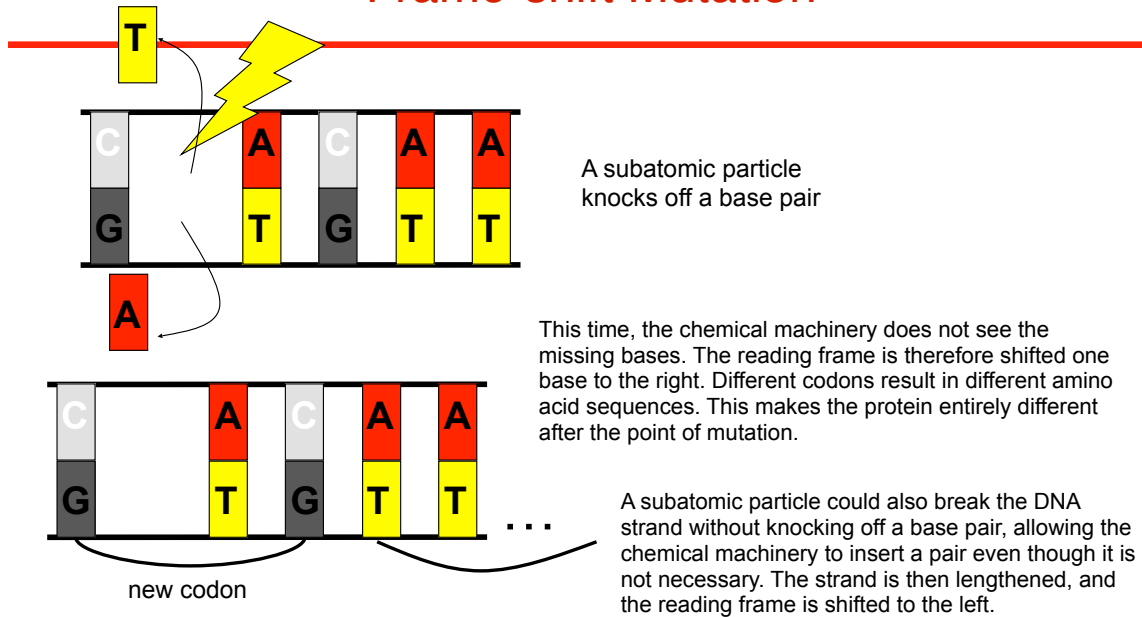
Nonsense Mutations



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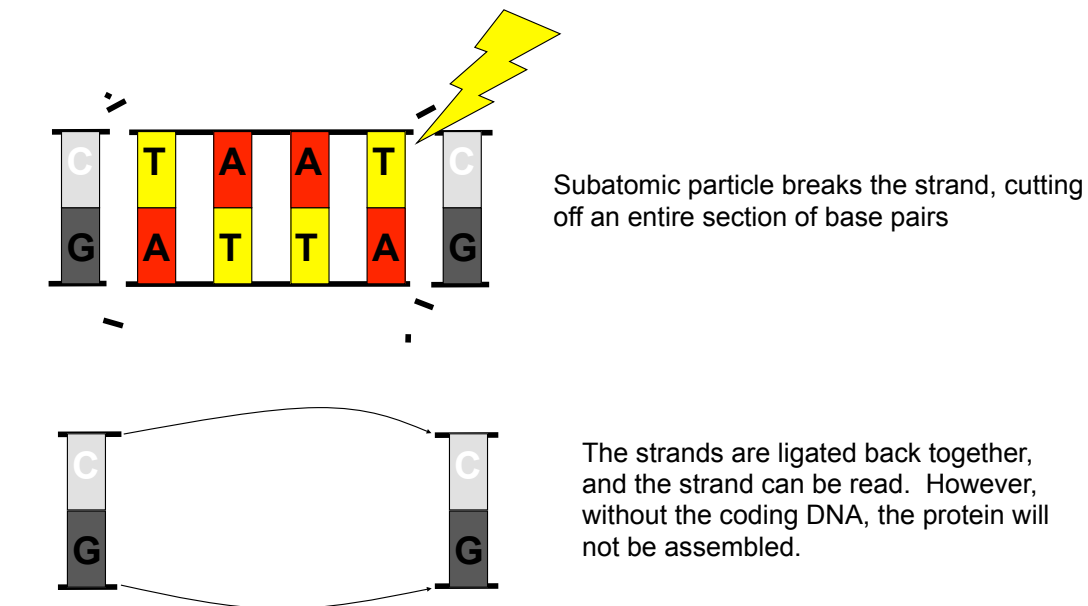
Frame-shift Mutation



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Deletion Mutations



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Effects of Ionizing Radiation

Difference between “dose” and “dose rate” —

- Dose rate = dose per unit time
- Physical dose rate (Gr/s, Gr/hr, mGr/yr, ...)
- Biological dose rate (Sv/s, Sv/hr, mSv/yr, ...)

Effects of Nuclear War

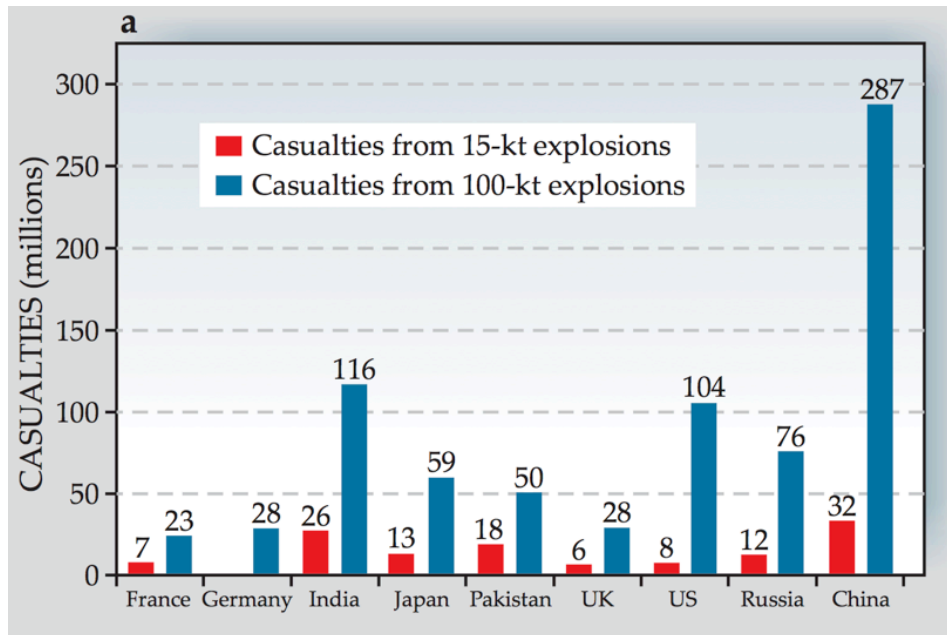
Nuclear War Models

U.S.-Russian war: 2200 x 2 weapons of 100-kt each = 440 Mt total

Regional nuclear war: 50 weapons of 15-kt each = 0.75 Mt total

Weapons are assumed to be targeted on industry.

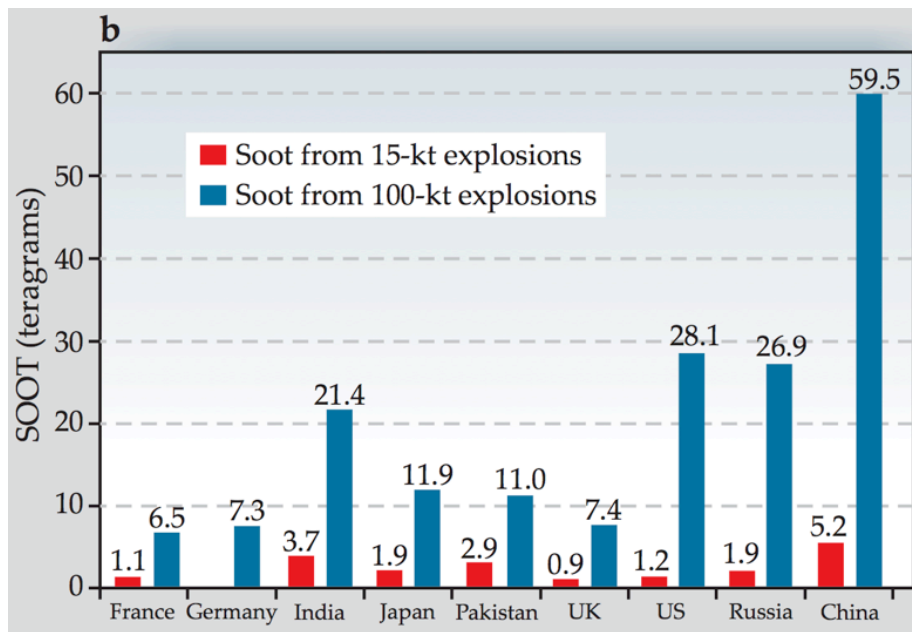
Effects of Nuclear War



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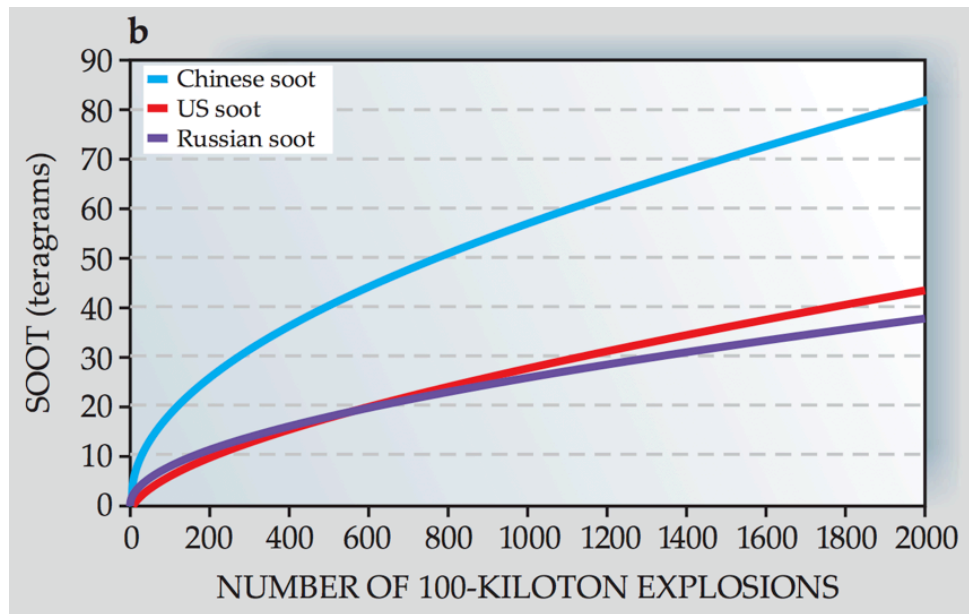
Effects of Nuclear War



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Effects of Nuclear War



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End of Topic

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