NATIONAL CENTER FOR CASE STUDY TEACHING IN SCIENCE

# Life in the Fat Lane:
## The Chemistry of Bear Hibernation

*by*
Scott J. Donnelly
Division of Science
Arizona Western College, Yuma, AZ

*In this case study you will learn about nature's metabolic marvel, the hibernating bear. A year in the life of a bear, especially those living at high northern latitudes such as in Alaska, is more or less equally divided into two parts. Half the year it is eating while the other half it is not. When a bear is not eating for such a long period of time how does it survive? Specifically, this case study looks at the organic chemistry pathway that allows a hibernating bear to survive during the long, foodless, calorie-deficient winter months. The types of questions asked in this case study include short answer, true/false, multiple choice, and rudimentary calculations.*

## Part I – To Eat or Not To Eat?

In the mammalian world, *Ursus arctos* (brown bear) and *Ursus americanus* (black bear) are both champion eaters and non-eaters. For up to half a year, starting from when bears emerge in the spring from their winter slumber until entering their winter den again in late autumn for another round of hibernation, North American bears roam the nutritional landscape searching for anything edible, preferably highly digestible fat- or protein-rich foods. But overall bears are not picky eaters.

Bears are omnivores. During the late spring to late autumn feeding frenzy, they chomp away at whatever calorie containing food is available. Generalists and opportunistic eaters, their choice of foods is based largely on availability. They eat a motley array of food types: newly emergent lush grasses, flowers, forbs, berries, roots and tubers, tree nuts, insects, and fresh or rotting elk, bison, deer, or fish meat (Mattson *et al.*, 1991; Mowat & Heard, 2006; Fortin *et al.*, 2013; Gunther *et al.*, 2014). Why eat so many different types of food? Quite simply, to prepare for the annual famine associated with hibernation.

The more bears eat, the fatter they get. The more fat a bear carries, the better its chances surviving the long, foodless winter while hibernating. For a pregnant mother bear, packing on the fat allows her to produce the quality and quantity of fat-rich milk for her cubs to survive (White *et al.*, 2017 and references therein). Furthermore, a chunky fat bear is a warm bear as a thick layer of fat is an effective strategy to reduce internal heat loss and maintain core body temperature so as to not die from hypothermia (Craighead & Craighead, 1972).

Bears are also undisputed champions at surviving a prolonged period of caloric deprivation. While hibernating, bears do not eat, drink, defecate, or urinate. Hibernation lasts from 100 to more than 150 consecutive days depending on where a bear lives. Bears in more northern latitudes hibernate longer than bears farther south. Evolution has endowed brown and black bears with the enviable metabolic capacity to starve themselves for a long period of time and still survive unharmed but of course very hungry.

How fat can bears get? Before investigating the miraculous chemistry bears utilize to survive hibernation, let's first take a quick look at an ursine heavyweight of 2020 known simply as Bear 747.

## Part II – Bear 747, the 2020 Ursine Heavyweight Champion of Fat Bear Week

Every summer brown bears take residence along or in the Brooks River in southwestern Alaska in Katmai National Park and Preserve (to learn more about the ecology, life histories, and habits of the coastal brown bears, see Bears of Brooks River 2022 at https://www.nps.gov/katm/learn/photosmultimedia/ebooks.htm). The population of bears feast on a steady buffet of protein and fat from the hundreds of thousands of Pacific sockeye salmon migrating during their annual epic journey from the salty waters of the northern Pacific Ocean to pristine freshwater spawning sites inland. Mature migrating salmon weigh from 5 to 7 pounds and most of that mass is muscle and fat. For a Katmai brown bear such as 747 the dinner bell rings loud; it is time to eat, and eat, and eat some more until the salmon migration is over (Hilderbrand *et al*., 1999).

How fat can brown bears of Katmai National Park and Preserve get? Bear 747, winner of the coveted title of the 2020 Fat Bear Week (FBW), is an example (Figure 1).

Conceptualized in 2014, FBW is a fun way to educate the public about this exquisitely muscled mammal. The ursine equivalent of the NCAA basketball March Madness bracket, FBW allows the public to vote on and ultimately select the fattest bear in a head-to-head photo competition (Figure 2). The winner in each round moves on to the next round until finally the fattest bear champion is crowned every October. In 2020 bear 747 was voted the fattest bear. Want to vote for this year's fattest Katmai National Park bear? Check out https://explore.org/fat-bear-week.

*Figure 1*. Bear 747, 2020 FBW champion. *Credit:* NPS Photo/N. Boak, PD, https://www.flickr.com/photos/katmainps/50433112622.


*Figure 2*. 2020 FBW bracket. *Credit:* https://www.katmaiconservancy.org/fat-bear-week-2020/.

## Part III – The Miraculous Metabolic Chemistry of Hibernation Commences

How do hibernating bears stay alive for up to 150+ consecutive days without eating or drinking? Bears emerge from winter dens in the spring 20–30% lighter than when they entered the den in late autumn (White, 2017). The loss in body mass is due entirely to "eating" their fat reserves. Bears break down stored fat reserves to supply the necessary energy to keep breathing, the heart pumping blood, and maintain the core body temperature as too far a drop could result in death from hypothermia. To stay alive during prolonged hibernation a bear must make some life-saving metabolic adjustments. The first involves a sustained breakdown of the fat they packed on during the spring to autumn eating marathon. Let's begin looking at the chemistry of bear hibernation.

### *Questions*

1. True or false? The molecule below (Figure 3) is a polyunsaturated fat (triester) molecule, consisting of two unbranched saturated fatty acid side chains and one unbranched side chain with two sites of (conjugated) unsaturation (both with Z geometry).

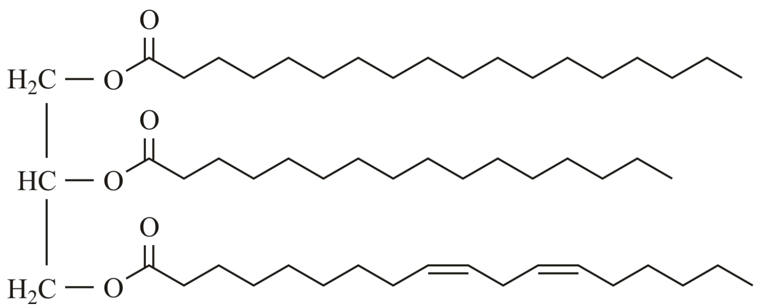

*Figure 3*. Molecule. *Credit:* E. Generalic, https://glossary.periodni.com/glossary.php?en=unsaturated+fat.

2. True or false? When the molecule above (Figure 3) is hydrolyzed, a molecule of glycerol and three molecules of fatty acid are produced. Three molecules of water are required.

3. True or false? Bears and other animals including humans use fats for long-term energy storage needs because fats are more reduced and hence can be oxidized for greater energy value than less reduced carbohydrates.

## Part IV – What's for Dinner?

Hibernating bears utilize fat catabolism to survive the long, foodless winter slumber. Fat catabolism occurs in four stages as illustrated below (Table 1). This case study focuses on the four chemical reactions in Stage 2. Each of these four reactions is described in detail in Part V. Questions related to the chemistry reactions in Stage 2 are also found in Part V.

*Table 1*. The four stages of fat catabolism.

| *Stage* | *Chemistry Happening* | *Notes* |
|---|---|---|
| 1 | fats $\rightarrow$ fatty acids | Catalyzed by lipase enzymes, the three esters groups per fat molecule are hydrolyzed to three smaller fatty acid molecules (side chain length varies) and glycerol. Stage 1 is digestion. |
| 2 | $\rightarrow$ acetyl-CoA $\rightarrow$ | Before being metabolized and then entering Stage 3 (the citric acid cycle), a fatty acid must be activated, first with ATP and then with the large carrier molecule coenzyme A, to form a fatty acyl-CoA, which then is degraded in four steps (one turn of the pathway) to produce acetyl-CoA and a now shorter fatty acyl-CoA per turn of the pathway. This happens until all the carbons in the original fatty acid have been converted to acetyl-CoA. This case study focuses on the chemical transformations in this stage. |
| 3 | Citric Acid Cycle $\rightarrow$ $CO_2$, $CO_2$ | The acetyl component of acetyl-CoA is oxidized inside cellular mitochondria to produce carbon dioxide and reduced coenzymes. The energy released in the citric acid cycle is used in the electron-transport chain to drive Stage 4. |
| 4 | $NADH \rightarrow 3ATP + NAD^+$<br>$FADH_2 \rightarrow 2ATP + FAD$ | The oxidation of the reduced coenzymes formed in Stage 3 leads to the oxidative phosphorylation of ADP to produce energy-rich ATP, the "energy currency" of the cell. ATP is "energy rich" on account of the "high energy" character of its phosphoanhydride bonds. The synthesis of ATP from ADP and phosphate ion ($HOPO_3^{-2}$) is endergonic, $\Delta G = (+)$. |

## Part V – A Little Plus a Little Plus a Little Many Times Equals A Lot

With help from lipase enzymes, a hibernating bear systematically breaks down stored fat reserves via hydrolysis into simpler free fatty acids. Side chain lengths vary. The fatty acids are then activated for metabolic use by forming a thioester linkage with the large carrier molecule coenzyme A (fatty acid + coenzyme A = fatty acyl-CoA). What follows is a detailed look at the four enzyme-catalyzed reactions (steps) and also coenzyme dependent reactions of fatty acids that occur and that eventually lead to the production of ATP, the "energy currency" of the cell.

Questions in this section are identified using the following format for the four reactions (steps) in Stage 2:

S1, Q1 = Step 1, Question 1;

S1, Q2 = Step 1, Question 2;

S2, Q3 = Step 2, Question 3; and so on.

So let's find out more about the four reactions/steps that activated fatty acids (fatty acid + CoA) undergo that allow hibernating bears to survive from "eating" their fat reserves for consecutive months.

### *Step 1*

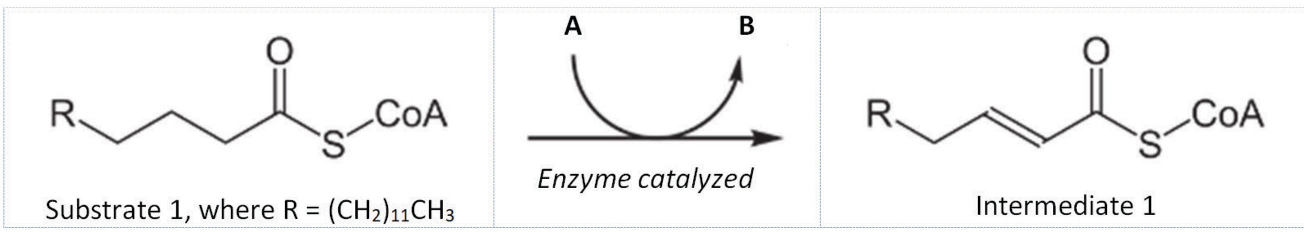


*Figure 4*. The first step or reaction in Stage 2 of fat catabolism.

S1, Q1: What is the overall length (total number of carbons) of the fatty acid component (moiety; including the carbonyl group) of the fatty acyl-CoA (Substrate 1)?

S1, Q2: Excluding the thioester carbon, is the fatty acid moiety of Substrate 1 saturated or unsaturated?

S1, Q3: According to the reaction chemistry is Substrate 1 oxidized, reduced, or neither?

S1, Q4: The overall change in the Index of Hydrogen Deficiency (IHD) for the reaction ($\Delta IHD_{rxn}$) is:

a. 0 b. –2 c. –1 d. +1 e. +2 f. none of the choices

As indicated in the reaction scheme (Figure 4 above), the formation of Intermediate 1 from Substrate 1 requires some "helpers": an enzyme and a redox prosthetic group, A, which is transformed into B upon the formation of Intermediate 1. Answer the three sub-questions (a–c) below.

S1, Q5a: In Step 1, is A an oxidizing agent, reducing agent, or neither?

S1, Q5b: Is B the more oxidized or the more reduced form of A? Or are A and B the same molecule?

S1, Q5c: Enzymes are classified based on how they interact with the substrate. Substrate bonds are broken and new bonds are made resulting in the formation of a product (or intermediate in a multi-step synthesis). Based on the reaction chemistry in Step 1, the enzyme is a:

a. hydrolase  b. isomerase  c. dehydrogenase  d. hydratase

e. thiolase  f. transferase  g. none of the choices

S1, Q6: In Intermediate 1 the C=C bond (formed between the alpha, α, and beta, β, carbons, which are the second and third carbons respectively of the fatty acid component) has *trans* rather than *cis* geometry. Offer an explanation for the preference in molecular geometry for this unsaturated site.

S1, Q7: Let's take a closer look at the structures of the prosthetic groups A and B in Step 1. The redox active moieties of the most reduced and most oxidized forms of the coenzyme prosthetic group involved in Step 1 are shown below. One of the structures is A and the other structure is B. Based on the reaction chemistry of Step 1, which structure below, (1) or (2), is A? (*Hint:* See S1, Q3.)

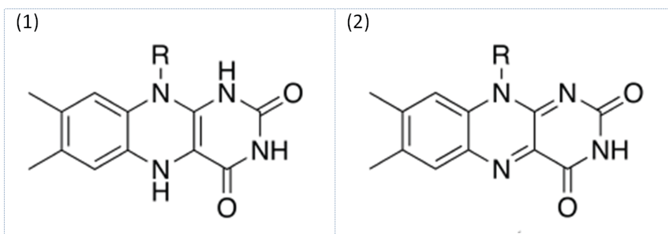


*Figure 5*. Which structure is A?

## *Step 2*

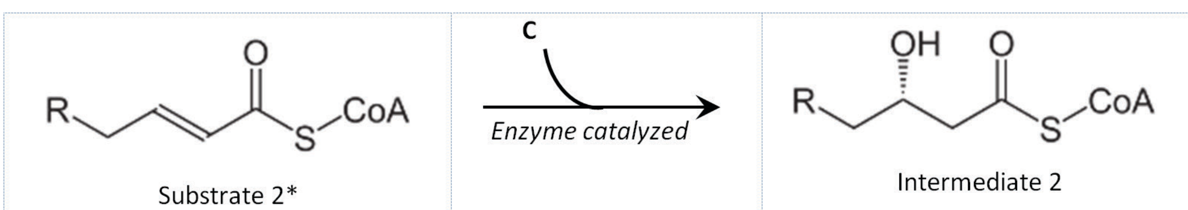


*Figure 6*. The second step or reaction in Stage 2 of fat catabolism. The asterisk (*) indicates that Intermediate 1 becomes Substrate 2.

S2, Q1: What is the overall length (total number of carbons, including the carbonyl group) of the α,β-unsaturated fatty acid moiety of the fatty acyl-CoA (Substrate 2)?

S2, Q2: Is the overall length of the α,β-unsaturated fatty acid moiety of the fatty acyl-CoA in Substrate 2 greater than, less than, or equal to that in Substrate 1?

S2, Q3: Based on the net reaction for Step 2, identify the molecular formula of reagent C.

S2, Q4: Determine if the following statement below is true or false: *In the reaction the fatty acid moiety of Substrate 2 changed from unsaturated to saturated. In doing so the ideal bond angle, hybridization, and structural geometries for both α and β carbons changed from 120° to 109.5°, from $sp^2$ to $sp^3$, and from trigonal pyramidal to tetrahedral.*

S2, Q5: Based on the reaction chemistry of Step 2 complete the table below.

| $\Delta IHD_{rxn}$ | *Configuration β carbon: R or S ?* | *Enzyme type** | *Reaction type#* |
|---|---|---|---|
| | | | |

*: Choices, A = hydrolase, B = hydrogenase, C = dehydratase, D = lipase, E = dehydrogenase, F = hydratase
#: Choices, 1 = substitution, 2 = isomerization, 3 = addition, 4 = elimination, 5 = rearrangement

S2, Q6: As indicated Step 2 is enzyme-dependent. And only one product (Intermediate 2) is formed in this enzyme-dependent reaction. But if the reaction occurred without an enzyme, then other products are possible for this type of reaction involving a C=C bond. Offer a reason why Step 2 requires the specificity of an enzyme. Also, draw the structure of two other possible products that theoretically could form but do not.

## *Step 3*

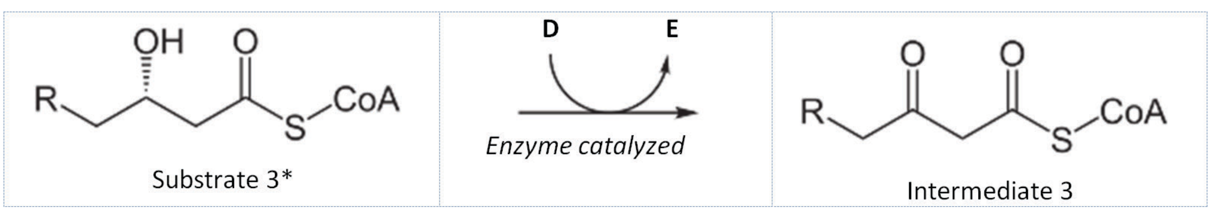


*Figure 7*. The third step or reaction in Stage 2 of fat catabolism. The asterisk (*) indicates that Intermediate 2 becomes Substrate 3.

S3, Q1: What is the overall length (total number of carbons including the carbonyl group) of the fatty acid moiety of the fatty acyl-CoA (Substrate 3)?

S3, Q2: Is the overall length of the fatty acid moiety of the fatty acyl-CoA in Substrate 3 greater than, less than, or equal to that in Substrate 2?

S3, Q3: Excluding the thioester carbon, is the fatty acid moiety of Substrate 3 saturated (S) or unsaturated (US)?

S3, Q4: Based on Step 3's reaction chemistry answer the series of questions below.

(a) Is the α carbon oxidized, reduced, or neither? How about the prosthetic group D?

(b) What is the change in the Index of Hydrogen Deficiency for the reaction. $\Delta IHD_{rxn}$?

(c) Which of the choices below (1–8), if any, accurately describe the change(s) to the β carbon? (Circle)

1. From saturated (*sp*$^3$-hybridization and chiral) to unsaturated (*sp*$^2$-hybridization); $\angle C_\alpha–C_\beta–O \rightarrow$ 109.5° to 120° (ideal); from trigonal planar to tetrahedral geometry (where $C_\beta$ = central atom).
2. From unsaturated (*sp*-hybridization) to unsaturated (*sp*$^2$-hybridization and achiral); $\angle C_\alpha–C_\beta–O \rightarrow$ 120° to 180° (ideal); from tetrahedral to trigonal pyramidal geometry (where $C_\beta$ = central atom).
3. From saturated (*sp*$^3$-hybridization and chiral) to unsaturated (*sp*$^2$-hybridization); $\angle C_\alpha–C_\beta–O \rightarrow$ 109.5° to 120° (ideal); from tetrahedral to trigonal pyramidal geometry (where $C_\beta$ = central atom).
4. From saturated (*sp*$^3$-hybridization and chiral) to unsaturated (*sp*$^2$-hybridization); $\angle C_\alpha–C_\beta–O \rightarrow$ 109.5° to 120° (ideal); from tetrahedral to trigonal planar geometry (where $C_\beta$ = central atom).
5. From unsaturated (*sp*$^2$-hybridization) to saturated (*sp*$^3$-hybridization and chiral); $\angle C_\alpha–C_\beta–O \rightarrow$ 109.5° to 120° (ideal); from tetrahedral to trigonal planar geometry (where $C_\beta$ = central atom).
6. From unsaturated (*sp*$^3$-hybridization) to saturated (*sp*$^2$-hybridization and achiral); $\angle C_\alpha–C_\beta–O \rightarrow$ 120° to 109.5° (ideal); from trigonal planar to tetrahedral geometry (where $C_\beta$ = central atom).
7. From saturated (*sp*$^2$-hybridization and chiral) to unsaturated (*sp*$^3$-hybridization); $\angle C_\alpha–C_\beta–O \rightarrow$ 109.5° to 180° (ideal); from tetrahedral to linear geometry (where $C_\beta$ = central atom).
8. None of the previous choices.

S3, Q5: Which statement is true with respect to the reaction chemistry of Step 3?

a. The chiral primary alcohol group in Substrate 3 is oxidized to a ketone resulting in the formation of a β-keto thioester. The prosthetic group D is reduced (and hence is an oxidizing agent). Intermediate 3 is more unsaturated than Substrate 3. $\Delta IHD_{rxn}$ = +1.
b. The chiral secondary alcohol group in Substrate 3 is reduced to a ketone resulting in the formation of a β-keto thioester. The prosthetic group D is oxidized (and hence is a reducing agent). Intermediate 3 is more unsaturated than Substrate 3. $\Delta IHD_{rxn}$ = −1.
c. The chiral secondary alcohol group in Substrate 3 is oxidized to a ketone resulting in the formation of a β-keto thioester. The prosthetic group D is reduced (and hence is an oxidizing agent). Intermediate 3 is less unsaturated than Substrate 3. $\Delta IHD_{rxn}$ = −1.
d. The chiral tertiary alcohol group in Substrate 3 is reduced to a ketone resulting in the formation of a β-keto thioester. The prosthetic group D is reduced (and hence is an oxidizing agent). Intermediate 3 is more unsaturated than Substrate 3. $\Delta IHD_{rxn}$ = +1.
e. The chiral secondary alcohol group in Substrate 3 is oxidized to a ketone resulting in the formation of a β-keto thioester. The prosthetic group D is reduced (and hence is an oxidizing agent). Intermediate 3 is more unsaturated than Substrate 3. $\Delta IHD_{rxn}$ = +1.
f. none of the choices

S3, Q6: Enzymes are classified based on how they interact with the substrate. Substrate bonds are broken and new bonds are made resulting in the formation of a product (or intermediate in a multi-step synthesis). Based on the reaction chemistry in Step 3, the enzyme is a:

a. thiolase b. isomerase c. transferase d. dehydrogenase

e. hydrolase f. dehydratase g. none of the choices

S3, Q7: As indicated, Step 3 requires some "helpers" (see Figure 7 above): an enzyme and a redox prosthetic group, D, which is transformed into E upon the formation of Intermediate 3. The redox active moieties of the most reduced and most oxidized forms of the coenzyme prosthetic group involved in Step 3 are shown below. One of the structures is D and the other structure is E. Based on the Step 3 reaction chemistry described, which choice, (1) or (2), is E?

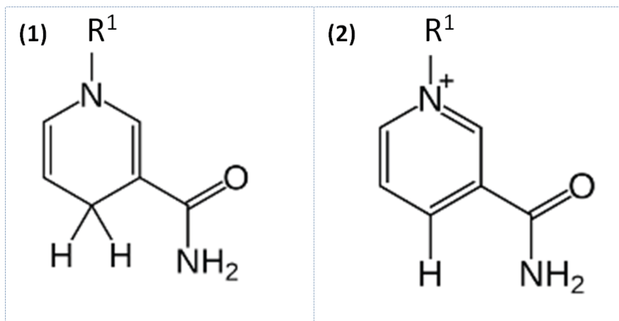


*Figure 8*. Which structure is E? (Note that $R^1$ is identical in both forms.)

### *Step 4*

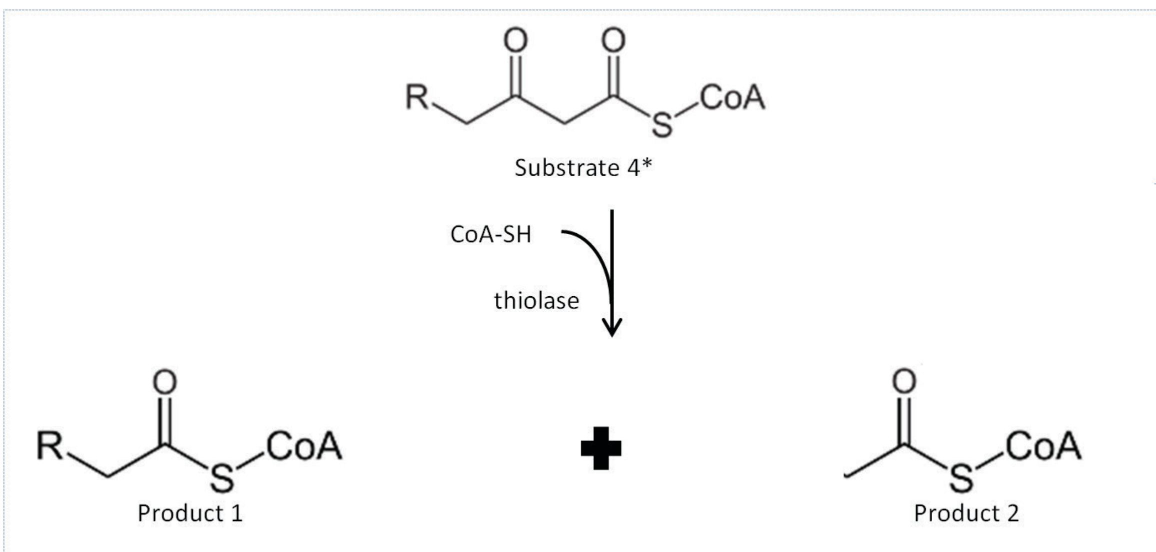


*Figure 9*. The fourth step or reaction in Stage 2 of fat catabolism. The asterisk (*) indicates that Intermediate 3 becomes Substrate 4. Note that there are two kinds of thiolases: degradative and biosynthetic. Note further that the products are formed from nucleophilic addition to the electrophilic β-carbonyl group followed by a reverse-Claisen condensation reaction.

S4, Q1: What is the overall length (total number of carbons including the carbonyl group) of the β-keto fatty acid moiety of the fatty acyl-CoA (Substrate 4)?

S4, Q2: Is the overall length of the β-keto fatty acid moiety of the fatty acyl-CoA in Substrate 4 greater than, less than, or equal to that in Substrate 3?

S4, Q3: Both the ketone carbon and the thioester carbon in Substrate 4 are electrophilic. But the CoASH adds to the ketone carbon and not to the thioester carbon. Presuming that an amino acid in the side chain of the thiolase enzyme is not involved in the nucleophilic addition, offer an explanation for the preferential nucleophilic addition of the "free" CoASH to the electrophilic carbon of the ketone rather than to the electrophilic carbon of the thioester.

S4, Q4: Is the overall length of the fatty acid moiety of the fatty acyl-CoA in Product 1 greater than, less than, or equal to that in Substrate 4?

S4, Q5: If your answer to S4,Q4 is either "greater than" or "less than," then indicate by how many carbons the fatty acid moiety is longer or shorter in Product 1 compared to Substrate 4.

As mentioned at the beginning of Part V the transformation of a fatty acyl-CoA involves four steps. Formation of Product 1 and Product 2 is the end of Step 4. This means the original fatty acyl-CoA has undergone one complete turn of transformation (beginning of Step 1 to product formation in Step 4). And at the end of this one complete turn something is structurally different about the original fatty acyl-CoA (Substrate 1) compared to Product 1 (the end of Step 4). Let's take this knowledge and apply it to the following true/false questions.

S4,Q6: Determine if each statement below is true or false.

(a) The thiolase in Step 4 acts as a biosynthetic enzyme. (True or false?)

(b) In one complete turn of a fatty acid two molecules are formed: a molecule of acetyl-CoA and a molecule of a fatty acyl-CoA. The latter is shorter by two carbon atoms relative to the original fatty acyl-CoA (Substrate 1, Figure 10 below). (True or false?)

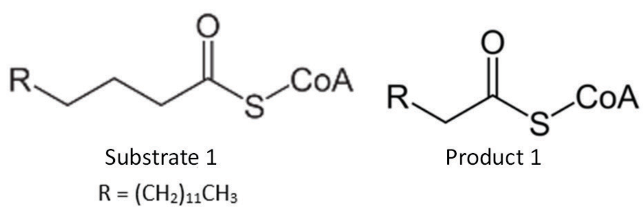


*Figure 10.* True or false?

(c) In the example described in this case study, the fatty acid moiety of the original fatty acyl-CoA (Substrate 1) had a total number of 16 carbons. The fatty acid moiety of the fatty acyl-CoA formed in Step 4 (Product 1 in Figure 10, above) of the first turn of the pathway has 14 total carbons. (True or false?)

(d) The shortened fatty acyl-CoA (Product 1) formed at the end of Step 4 of the first turn has 14 carbons. It can now re-enter (Step 1) into the fatty acid catabolism pathway. At the end of a second turn a molecule of acetyl-CoA again is produced along with a molecule of a fatty acyl-CoA that now has twelve carbons. This 12 carbon fatty acyl-CoA formed after a second turn now re-enters the pathway again at Step 1 and at the end of a third turn a molecule of acetyl-CoA again is produced along with a molecule of a fatty acyl-CoA that has ten carbons. This spiraling degradative pathway involving the repeated loss of two-carbon fragments (as acetyl-CoA) for each complete turn can continue until all the original fatty acid carbons have been converted into acetyl-CoA. (True or false?)

(e) Each complete turn of the fatty acid catabolic pathway produces a fatty acyl-CoA that is two carbons shorter than the fatty acyl-CoA at the start of a turn. Suppose there is a fatty acid with molecular formula $CH_3(CH_2)_{10}CO_2H$. This fatty acid is then coupled to coenzyme A and the degradative oxidative pathway begins. Six complete turns are necessary to produce six acetyl-CoA molecules. (True or false?)

The catabolic fatty acid pathway is summarized below (Figure 11). The four-step pathway is for even numbered, unbranched, saturated fatty acids. Odd-numbered and/or unsaturated fatty acids require additional steps. Subscript *x* can be 10, 12, 14, 16, or 18 to give an overall, even numbered fatty acid component linked via a sulfur bond to CoA.

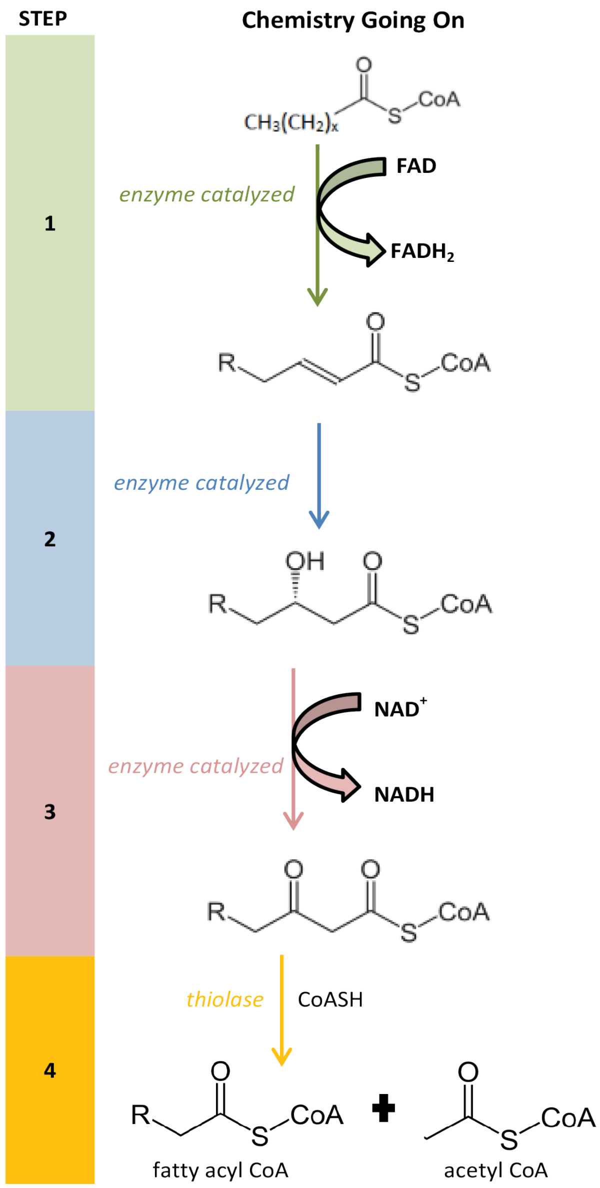


*Figure 11*. Summary diagram of catabolic fatty acid pathway.

S4, Q7: Suppose the fatty acid $C_{18}H_{36}O_2$ enters into the fatty acid catabolic pathway and is completely catabolized. For each of the following bulletted items, indicate the total number that result for this completely catabolized fatty acid on a per molecule basis.

Total number of ...

- Turns:
- $NAD^+$ required: _____
- $FADH_2$ produced: _____
- acetyl CoA produced: _____
- ATP ultimately generated: _____
  (Assume 1.5 ATP generated per $FADH_2$ formed and 2.5 ATP generated per NADH formed.)
- Coenzyme A required: _____

This is not all the ATP generated from the $C_{18}H_{36}O_2$ fatty acid. The acetyl-CoA produced now enters into the citric acid cycle where even more ATP is produced. The ATP produced from fat catabolism (Stage 2) plus from the citric acid cycle keeps a bear alive during months and months of voluntary starvation during hibernation.

## Conclusion

Without the accumulation of fat reserves, followed by the hydrolysis of the fats, and then the subsequent β-oxidation of saturated fatty acids (coupled to the citric acid cycle), a hibernating bear would die. Humans and all other mammals utilize the β-oxidation pathway too but there is not enough fat to sustain the necessary metabolic maintenance to remain alive for as long a period of time compared to a bear.

A hibernating bear is a metabolic and evolutionary marvel of nature. It seems inconceivable at first glance to believe that an animal so large does not die when it does not eat, drink, or defecate for more than 100 consecutive days. The chemistry involved in keeping a hibernating bear alive during a prolonged period of zero calorie input is a marvel as well. In fact, it is the reason why the bear survives. Though the breaking down of saturated fats looks complicated when viewed in its entirety—with all the arrows pointing this way and that way along with changes to molecular structures—when the reactions are viewed individually it becomes much simpler to understand. And the elegance of the metabolic system becomes more apparent. On the most basic level, a hibernating bear's survival is based on a simple statement repeated over and over in chemistry courses: *certain bonds are broken and certain new bonds are made.* And once one cycle of successive bond breaking and bond making ends, then another new cycle begins. For a hibernating bear, this means it survives.

## References

Craighead, F.C. & J.J. Craighead. (1972). Grizzly bear prehibernation and denning activities as determined by radiotracking. *Wildlife Monographs* 32: 3–35. <https://www.jstor.org/stable/3830494>

Fortin, J.K., C.C. Schwartz, K.A. Gunther, J.E. Teisberg, M.A. Haroldson, M.A. Evans, & C.T. Robbins. (2013). Dietary adjustability of grizzly bears and American black bears in Yellowstone National Park. *The Journal of Wildlife Management* 77(2): 270–81. <https://doi.org/10.1002/jwmg.483>

Gunther, K.A., R.R. Shoemaker, K.L. Frey, M.A. Haroldson, S.L. Cain, F.T. van Manen, and J.K. Fortin. 2014. Dietary breadth of grizzly bears in the Greater Yellowstone Ecosystem. *Ursus* 25(1): 60–72. <https://doi.org/10.2192/URSUS-D-13-00008.1>

Hellgren, E.C. (1998). Physiology of hibernation in bears. *Ursus* 10: 467–77. <https://www.jstor.org/stable/3873159>

Hilderbrand, G.V., C.C. Schwartz, C.T. Robbins, M.E. Jacoby, T.A. Hanley, S. Arthur, & C. Servheen. (1999). The importance of meat, particularly salmon, to body size, population productivity, and conservation of North American grown bears. *Canadian Journal of Zoology* 77(1): 132–8. <https://doi.org/10.1139/cjz-77-1-132>

Mattson, D.J., B.M. Blanchard, & R.R. Knight. (1991). Food habits of Yellowstone grizzly bears, 1977–1987. *Canadian Journal of Zoology* 69: 1619–29.

Mowat, G. and D.C. Heard. (2006). Major components of grizzly bear diet across North America. *Canadian Journal of Zoology* 84(3): 473–89. <https://doi.org/10.1139/z06-016>

Nelson, R.A. (1987). Black bears and Polar bears: still metabolic marvels. *Mayo Clinic Proceedings* 62(9): 850–3. <https://doi.org/10.1016/s0025-6196(12)62341-6>

Rogers, L.L. (1981). A bear in its lair. *Natural History Magazine* 90(10): 64–70.

Staff of Katmai National Park and Preserve, National Park Service, U.S. Department of the Interior.. (2022). Bears of Brooks River 2022: a guide to their identification, lives, and habits. <https://www.nps.gov/katm/learn/photosmultimedia/ebooks.htm>

Stenvinkel, P., A.H. Jani, and R.J. Johnson. (2013). Hibernating bears (Ursidae): metabolic magicians of definite interest for the nephrologist. *Kidney International* 83(2): 207–12. <https://doi.org/10.1038/ki.2012.396>

Tøien, O., J. Blake, D.M. Edgar, D.A. Grahn, H.C. Heller, and B.M. Barnes. (2011). Hibernation in black bears: independence of metabolic suppression from body temperature. *Science* 331(6019): 906–9. <https://doi.org/10.1126/science.1199435>

White, P.J., K.A. Gunther, & F. T. van Manen, eds. (2017). *Yellowstone Grizzly Bears: Ecology and Conservation of an Icon of Wildness*. Yellowstone Forever, Yellowstone National Park and U.S. Geological Survey, Northern Rocky Mountain Science Center. <https://www.nps.gov/yell/learn/nature/upload/Yellowstone_Grizzlies_Web.pdf>