Next, let us consider stochastic models for perishable products, also called "newsvendor problem".

We consider/assume:

- A single perishable product, e.g., newspaper, food, flowers, seasonal goods such as clothing (but also, e.g., airline reservations)
- single time period
- at the end of period, product has salvage value (e.g., selling clothes out of season at a discount)
- no initial inventory
- decision variable y = # of items to stock
- the demand D is a random variable (we will need to make reasonable assumptions for its probability distribution)

- K = setup cost, irrelevant here (exactly one order is placed)
- c = unit cost of purchasing/producing
- h = holding cost per item = cost of storage − salvage value
- p = shortage cost (penalty) per item, e.g., lost revenue or lost customer goodwill

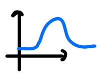
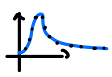
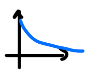
The amount sold is $\min\{D, y\} = \begin{cases} D & \text{if } D < y, \\ y & \text{if } D \geq y. \end{cases}$

The cost is $C(D,y) = \underbrace{cy}_{\text{order cost}} + \underbrace{p \max\{0, D-y\}}_{\substack{\text{penalty} \\ = \begin{cases} 0 & \text{if } D<y, \\ p(D-y) & \text{if } D>y. \end{cases}}} + \underbrace{h \max\{0, y-D\}}_{\substack{\text{holding cost} \\ = \begin{cases} 0 & \text{if } D>y \text{ (all sold)} \\ h(y-D) & \text{if } D<y \text{ (leftovers)} \end{cases}}}$

Goal: minimize expected cost, given some probability distribution $\underbrace{P_D(d)}_{\text{probability that demand} = d}$ for the demand.

Expected cost $\mathbb{E}[C](y) = \sum_{d=0}^{\infty} C(d,y)\, P_D(d)$.

How do we model $P_D(d)$?

- Select a good distribution based on theoretical considerations, e.g.,
  - Gaussian  (continuous)
  - Poisson  (discrete)
  - exponential  (continuous)
- Choose parameters such as mean and variance from historical data or good guesses.

Additionally: If d ranges over large number of values, it makes sense to approximate it by a continuous probability distribution $\varphi(d)$.

Then
$$
\begin{aligned}
\mathbb{E}[C](y) &= \int_0^{\infty} C(x,y)\, \varphi(x)\, dx \\
&= \int_0^{\infty} \left[cy + p \max\{0, x-y\} + h \max\{0, y-x\} \right] \varphi(x)\, dx \\
&= cy \underbrace{\int_0^{\infty} \varphi(x) dx}_{\substack{=1, \text{ since} \\ \varphi \text{ is a probability} \\ \text{distribution}}} + p \underbrace{\int_0^{\infty} \max\{0, x-y\} \varphi(x) dx}_{= \int_y^{\infty} (x-y) \varphi(x) dx} + h \underbrace{\int_0^{\infty} \max\{0, y-x\} \varphi(x) dx}_{= \int_0^{y} (y-x) \varphi(x) dx}.
\end{aligned}
$$

$$\Rightarrow \mathbb{E}[C](y) = cy + p\int_y^\infty (x-y)\varphi(x)dx + h\int_0^y (y-x)\varphi(x)dx$$

Goal: minimize $\mathbb{E}[C](y)$. Thus we compute:

$$\frac{d\,\mathbb{E}[C](y)}{dy} = c + \underbrace{p\int_y^\infty (-\varphi(x))dx - p(x-y)\varphi(x)\Big|_{x=y}} + h\int_0^y \varphi(x)dx + h(y-x)\varphi(x)\Big|_{x=y}$$

Recall the Leibniz rule: $\dfrac{d}{dy}\displaystyle\int_{a(y)}^{b(y)} f(x,y)dx = \int_{a(y)}^{b(y)} \frac{\partial f(x,y)}{\partial y}dx + f(b(y),y)\frac{db(y)}{dy} - f(a(y),y)\frac{da(y)}{dy}$

boundaries also depend on y

$$\Rightarrow \frac{d\,\mathbb{E}[C](y)}{dy} = c - p\int_y^\infty \varphi(x)dx + h\int_0^y \varphi(x)dx$$

Let us introduce the cumulative distribution function $\Phi(y) := \int_0^y \varphi(x)dx$.

Note that $\Phi(\infty) = \int_0^\infty \varphi(x)dx = 1$ (all probabilities integrate up to 1).

$\Phi(y)$ tells us the probability that the demand is satified if we order y items.

Then $$\frac{d\,\mathbb{E}[C](y)}{dy} = c - p\Big(\underbrace{\int_0^\infty \varphi(x)dx}_{=1} - \underbrace{\int_0^y \varphi(x)dx}_{=\Phi(y)}\Big) + h\underbrace{\int_0^y \varphi(x)dx}_{=\Phi(y)}$$

$$= c - p + (p+h)\Phi(y) \overset{!}{=} 0$$

$$\Rightarrow \boxed{\Phi(y^*) = \frac{p-c}{p+h}}$$

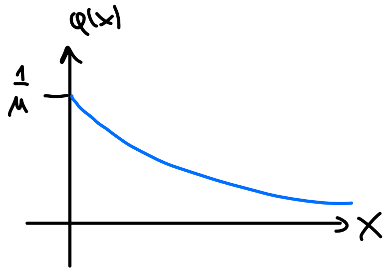
i.e., we should choose y^* s.t. this equation is satified.

solutions can be found algebraically or numerically / graphically

$\Phi(y^*)$ is called $\underbrace{\text{"optimal service level"}}_{}$.

= probability that demand is satisfied

Example: Assume exponential distribution $\varphi(x) = \frac{1}{\mu} e^{-\frac{x}{\mu}}$, with $\mu > 0$ the mean value.



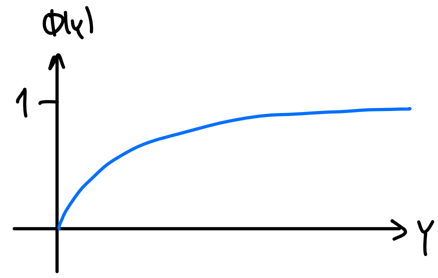
Note: μ is indeed the mean, since

change of variables: $\frac{x}{\mu} = y$

$$\mathbb{E}(X) = \int_0^\infty x\,\varphi(x)\,dx = \int_0^\infty \frac{x}{\mu} e^{-\frac{x}{\mu}}\,dx = \mu \int_0^\infty y e^{-y}\,dy$$

$$\overset{\text{integration by parts}}{=} \mu \underbrace{\left[-ye^{-y}\right]_0^\infty}_{=0} + \mu \int_0^\infty e^{-y}\,dy = -\mu e^{-y}\Big|_0^\infty = 0 - (-\mu) = \mu$$

Then $\Phi(y) = \int_0^y \frac{1}{\mu} e^{-\frac{x}{\mu}}\,dx = -e^{-\frac{x}{\mu}}\Big|_0^y = -e^{-\frac{y}{\mu}} + 1$



$$\Phi(y) = \frac{p-c}{p+h} \iff 1 - e^{-\frac{y}{\mu}} = \frac{p-c}{p+h} \iff e^{-\frac{y}{\mu}} = 1 - \frac{(p-c)}{p+h} = \frac{p+h}{p+h} - \frac{(p-c)}{p+h} = \frac{c+h}{p+h}$$

natural logarithm

$$\Rightarrow -\frac{y}{\mu} = \ln \frac{c+h}{p+h} \Rightarrow y = -\mu \ln \frac{c+h}{p+h} \overset{\ln\frac{a}{b} = -\ln\frac{b}{a}}{=} \mu \ln \frac{p+h}{c+h}$$

$\Rightarrow$ For exponential distribution with mean μ, the optimal order quantity is $\boxed{y^* = \mu \ln \frac{p+h}{c+h}}$.

Numerical example: For $\mu = 10\,000$, $c = 200$, $p = 450$, $\underbrace{h = -90}_{\text{a large salvage value can make } h \text{ negative.}}$, we find

$y^* \approx 11\,856$ (so 1856 items more than the average should be stocked).

Note that $\underbrace{\Phi(y^*) = \frac{450-200}{450-90} = 0.694}_{\text{optimal service level}}$ i.e., the demand is satisfied with 69.4% probability here.