A series of maximum entropy upper bounds of the differential entropy

https://arxiv.org/abs/1612.02954
https://www.lix.polytechnique.fr/~nielsen/MEUB/

Frank Nielsen\textsuperscript{1,2} Richard Nock\textsuperscript{3,4,5}
Frank.Nielsen@acm.org

\textsuperscript{1}École Polytechnique, France \textsuperscript{2}Sony Computer Science Laboratories, Japan
\textsuperscript{3}Data61, Australia \textsuperscript{4}ANU, Australia \textsuperscript{5}The University of Sydney, Australia

January 2017
Shannon’s differential entropy

\( X \sim p(x) \): continuous random variable, support
\[ \mathcal{X} = \{ x \in \mathbb{R} : p(x) > 0 \} \]

Shannon’s entropy quantifies amount of uncertainty [2]:

\[
H(X) = \int_{\mathcal{X}} p(x) \log \frac{1}{p(x)} \, dx = - \int_{\mathcal{X}} p(x) \log p(x) \, dx
\]  

(1)

logarithm: basis 2 (unit in \textit{bits}), basis \( e \) (\textit{nats}).

Differential entropy is strictly concave and:

- May be negative: \( X \sim N(\mu, \sigma) \), \( H(X) = \frac{1}{2} \log(2\pi e \sigma^2) < 0 \)
  when \( \sigma < \frac{1}{\sqrt{2\pi e}} \)

- May be infinite (unbounded): \( X \sim p(x) \) with \( p(x) = \frac{\log(2)}{x \log^2 x} \)
  for \( x > 2 \) (with support \( \mathcal{X} = (2, \infty) \))

- Closed forms [7, 9] for many distribution families, but the \textit{differential entropy of mixtures} usually does not admit closed-form expressions [10, 6]
Maximum Entropy Principle (MaxEnt)

Jaynes’ MaxEnt distribution principle [4, 5] (1957):
Infer a distribution given several moment constraints.
Constrained optimization problem:

\[
\max_p H(p) : E[t_i(X)] = \eta_i, \quad i \in [D] = \{1, \ldots, D\}. 
\] (2)

- When an iid sample set \( \{x_1, \ldots, x_s\} \) is given, we may choose, for example, the raw geometric sample moments 
  \( \eta_i = \frac{1}{s} \sum_{j=1}^{s} x_j^i \) for setting up the constraint \( E[X^i] = \eta_i \) (ie., taking \( t_i(X) = X^i \) in Eq. 2).

- The distribution \( p(x) \) maximizing the entropy under those moment constraints is unique and termed the MaxEnt distribution. The constrained optimization of Eq. 2 is solved by means of Lagrangian multipliers [8, 2].
MaxEnt and exponential families

MaxEnt distribution $p(x)$ belongs to a *parametric family* of distributions called an *exponential family* [1, 8, 3].

Canonical probability density function of an exponential family (EF):

$$p(x; \theta) = \exp \left( \langle \theta, t(x) \rangle - F(\theta) \right)$$

$\langle a, b \rangle = a^\top b$: scalar product

$\theta \in \Theta$: natural parameter

$\Theta$: natural parameter space

$t(x)$: sufficient statistics

$F(\theta) = \log \int p(x; \theta)dx$: log-normalizer [1]
Dual parameterizations of exponential families

A distribution $p(x; \theta)$ of an exponential family can be parameterized equivalently either using the

- natural coordinate system $\theta$,

- expectation coordinate system $\eta = E_{p(x;\theta)}[t(x)]$
  (also called moment coordinate system)

The two coordinate systems are linked by the Legendre transformation:

$$F^*(\eta) = \sup_{\theta} \{ \langle \eta, \theta \rangle - F(\theta) \}$$

$$\eta = \nabla F(\theta), \quad \theta = \nabla F^*(\eta)$$

In practice, when $F(\theta)$ is not available in closed-forms, conversion $\theta \leftrightarrow \eta$ is approximated numerically [8].
Differential entropy of exponential families

Closed-form when the dual Legendre convex conjugate function is in closed-form:

\[ H(p(x; \theta)) = -F^*(\eta(\theta)) \]

More general form when allowing an auxiliary carrier measure term [9]
Strategy to get MaxEnt Upper Bounds (MEUBs)

Rationale: Any other distribution with density $p'(x)$ different from the MaxEnt distribution $p(x)$ and satisfying all the $D$ moment constraints $E[t_i(X)] = \eta_i$ have smaller entropy:

$$H(p'(x)) \leq H(p(x)) \text{ with } p(x) = p(x; \theta).$$

Recipe for building MaxEnt Upper Bounds on arbitrary density $q(x)$:

- Choose sufficient statistics $t_i(x)$ so that the differential entropy $H(p(x; \eta))$ of the induced maxent distribution $p(x; \theta)$ is in closed-form (or can be unbounded easily)

- Compute the moment coordinates $\eta_i = E_q[t_i(x)]$, and deduce that $H(q(x)) \leq H(p(x; \eta))$
Absolute Monomial Exponential Family

\[ p_l(x; \theta) = \exp \left( \theta |x|^l - F_l(\theta) \right), \quad x \in \mathbb{R} \quad (4) \]

for \( \theta < 0 \).

Exponential family \( (t(x) = |x|^l) \) with log-normalizer:

\[ F_l(\theta) = \log 2 + \log \Gamma \left( \frac{1}{l} \right) - \log l - \frac{1}{l} \log(-\theta), \quad (5) \]

\( \Gamma(u) = \int_0^\infty x^{u-1} \exp(-x)dx \) generalizes the factorial:

\( \Gamma(n) = (n - 1)! \) for \( n \in \mathbb{N} \)
Differential entropy of AMEFs

The entropy expressed using the $\theta$-parameter is:

\[
H_l(\theta) = \log 2 + \log \Gamma \left( \frac{1}{l} \right) - \log l + \frac{1}{l} \left( 1 - \log(-\theta) \right),
\]

\[
= a_l - \frac{1}{l} \log(-\theta),
\]  

(6)

where $a_l = \log 2 + \log \Gamma \left( \frac{1}{l} \right) - \log l + \frac{1}{l}$.

The entropy expressed using the $\eta$-parameter is:

\[
H_l(\eta) = \log 2 + \log \Gamma \left( \frac{1}{l} \right) - \log l + \frac{1}{l} \left( 1 + \log l + \log \eta \right),
\]

\[
= b_l + \frac{1}{l} \log \eta,
\]  

(7)

with $b_l = \log \frac{2 \Gamma \left( \frac{1}{l} \right) (el)^{\frac{1}{l}}}{l}$.
A series of MaxEnt Upper Bounds (MEUBs)

For any continuous RV $X$, MaxEnt entropy Upper Bound (MEUB) $U_I$:

$$H(X) \leq H_I^n \left( E_X \left[ |X|^I \right] \right)$$

Are all UBs useful?
That is, can we build a RV $X$ so that $U_{I+1} < U_I$?
(Answer is yes!)
AMEF MEUBs for Gaussian Mixture Models

Density of a mixture model with $k$ components:

$$m(x) = \sum_{c=1}^{k} w_c p_c(x)$$

Gaussian distribution:

$$p_i(x) = p(x; \mu_i, \sigma_i) = \frac{1}{\sqrt{2\pi\sigma_i}} \exp \left( -\frac{(x - \mu_i)^2}{2\sigma_i^2} \right),$$

$\mu_i = E[X_i] \in \mathbb{R}$: mean parameter

$\sigma_i = \sqrt{E[(X_i - \mu_i)^2]} > 0$: standard deviation

To upper bound $H(X) \leq H_\eta^n (E_X [||X||])$, we need to compute the raw absolute geometric moments $E_X [||X||]$ for a GMM.
Raw absolute geometric moments of a GMM

Technical part (integration by parts and solving recurrence)

\[ A_l(X) = \begin{cases} 
\sum_{c=1}^{k} w_c \sum_{i=0}^{\lfloor \frac{l}{2} \rfloor} \binom{l}{2i} \mu_c^{l-2i} \sigma_c^{2i} 2^i \frac{\Gamma(\frac{1+2i}{2})}{\sqrt{\pi}} & \text{for even } l, \\
\sum_{c=1}^{k} w_c \sum_{i=0}^{l} \binom{n}{i} \mu_c^{l-i} \sigma_c^i \left( l_i \left( -\frac{\mu_c}{\sigma_c} \right) - (-1)^i l_i \left( \frac{\mu_c}{\sigma_c} \right) \right) & \text{for odd } l.
\end{cases} \]

where \( n!! \) denotes the double factorial: \( n!! = \prod_{k=0}^{\lfloor \frac{n}{2} \rfloor} (n-2k) = \sqrt{\frac{2^{n+1}}{\pi}} \Gamma(\frac{n}{2} + 1) \), and:

\[ l_i(a) = \frac{1}{\sqrt{2\pi}} \int_{a}^{+\infty} x^i \exp \left( -\frac{1}{2} x^2 \right) \, dx, \]

\[ = \frac{1}{\sqrt{2\pi}} \left( a^{i-1} \exp \left( -\frac{1}{2} a^2 \right) \right) + (i - 1) l_{i-2}(a), \]

with the terminal recursion cases:

\[ l_0(a) = 1 - \Phi(a) = \frac{1}{2} \left( 1 - \text{erf} \left( \frac{a}{\sqrt{2}} \right) \right) = \frac{1}{2} \text{erfc} \left( \frac{a}{\sqrt{2}} \right), \]

\[ l_1(a) = \frac{1}{\sqrt{2\pi}} \exp \left( -\frac{1}{2} a^2 \right). \]
AMEF for \( l = 1 \) is the Laplacian distribution

The differential entropy of a Gaussian mixture model

\[ X \sim \sum_{c=1}^{k} w_c p(x; \mu_c, \sigma_c) \]

is upper bounded by:

\[ H(X) \leq U_1(X) \]

\[ U_1(X) = \log \left( 2e \left( \sum_{c=1}^{k} w_c \left( \mu_c \left( 1 - 2\Phi \left( -\frac{\mu_c}{\sigma_c} \right) \right) + \sigma_c \sqrt{\frac{2}{\pi}} \exp \left( -\frac{1}{2} \left( \frac{\mu_c}{\sigma_c} \right)^2 \right) \right) \right) \). \]
Gaussian MEUB for a GMM \((l = 2)\)

AMEF for \(l = 2\) is the Gaussian distribution

The differential entropy of a GMM \(X \sim \sum_{c=1}^{k} w_c p(x; \mu_c, \sigma_c)\) is upper bounded by:

\[
H(X) \leq U_2(X) = \frac{1}{2} \log \left( 2\pi e \sum_{c=1}^{k} w_c (\mu_c - \bar{\mu})^2 + \sigma_c^2 \right),
\]

with \(\bar{\mu} = \sum_{c=1}^{k} w_c \mu_c\).
Vanilla approximation method: Monte-Carlo

Estimate $H(X)$ using Monte-Carlo (MC) stochastic integration:

$$\hat{H}_s(X) = -\frac{1}{s} \sum_{i=1}^{s} \log p(x_i), \quad (8)$$

where $\{x_1, \ldots, x_s\}$ is an iid set of variates sampled from $X \sim p(x)$.

MC estimator $\hat{H}_s(X)$ is consistent:

$$\lim_{s \to \infty} \hat{H}_s(X) = H(X)$$

(convergence in probability)

However, no deterministic bound, can be above or below true value.
**Experiments: Laplacian vs Gaussian MEUBs**

$k = 2$ to 10 for $\mu_i, \sigma_i \sim_{iid} U(0, 1)$, averaged on 1000 trials.

<table>
<thead>
<tr>
<th>$k$</th>
<th>Average error</th>
<th>Percentage of times $U_1(X) &lt; U_2(X)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.5401015778688498</td>
<td>32.7</td>
</tr>
<tr>
<td>3</td>
<td>2.7397146972652484</td>
<td>39.2</td>
</tr>
<tr>
<td>4</td>
<td>3.4333962273074774</td>
<td>47.9</td>
</tr>
<tr>
<td>5</td>
<td>0.9310683623797987</td>
<td>49.9</td>
</tr>
<tr>
<td>6</td>
<td>0.5902956910979954</td>
<td>52.1</td>
</tr>
<tr>
<td>7</td>
<td>0.7688142345093779</td>
<td>53.2</td>
</tr>
<tr>
<td>8</td>
<td>0.2982994538560814</td>
<td>53.8</td>
</tr>
<tr>
<td>9</td>
<td>0.1955843679792208</td>
<td>56.8</td>
</tr>
<tr>
<td>10</td>
<td>0.1797637053023196</td>
<td>59.9</td>
</tr>
</tbody>
</table>

Important to *recenter the GMMs* so that they have zero expectation (as AMEFs): This does not change the entropy. If not, the 30%+ rates fall significantly to less than 10%.
Are all AMEF MEUBs useful for GMMs?

- For zero-centered GMMs, only Laplacian or Gaussian MEUB is useful,

- For arbitrary GMMs, each bound can be the tightest one ($k = 2$, with GMM mean 0 and two symmetric components with small standard deviation).
Zero-centered GMMs

\[ U_1(X) < U_2(X) \text{ iff} \]

\[ \log 2e \sqrt{\frac{2}{\pi}} \bar{\sigma}_1 \leq \log \sqrt{2\pi e \bar{\sigma}_2}. \]

\[ \frac{\bar{\sigma}_1}{\bar{\sigma}_2} \leq \frac{\pi}{2\sqrt{e}} \approx 0.9527 \]

\( \bar{\sigma}_1: \) arithmetic weighted mean, \( \bar{\sigma}_2 = \sqrt{\sum_{i=1}^{k} w_i \sigma_i^2} \): quadratic mean
weighted quadratic mean dominates weighted arithmetic mean:
\[ \frac{\bar{\sigma}_1}{\bar{\sigma}_2} \leq 1. \]

\( k = 1: \) \( \sigma > \frac{2\sqrt{e}}{\pi} \) (ie., \( \sigma > 1.0496 \))
Zero-centered GMMs: $U_{l+2} < U_l$?

Geometric raw (even) moments coincide with the central (even) geometric moments

$$H(X) \leq H^\eta_l (A_l(X)) = b_l + \frac{1}{l} \log z_l + \log \bar{\sigma}_l,$$

$$E_X[X^l] = 2^l \frac{l}{2} \frac{\Gamma\left(\frac{1+l}{2}\right)}{\sqrt{\pi}} \left(\sum_{i=1}^{k} w_i \sigma_i^l \right) = A_l(X).$$

$\bar{\sigma}_l$: l-th power mean: $\bar{\sigma}_l = \left(\sum_{i=1}^{k} w_i \sigma_i^l \right)^{\frac{1}{l}}$

$$\frac{\bar{\sigma}_{l+2}}{\bar{\sigma}_l} \geq 1 \Rightarrow \log \frac{\bar{\sigma}_{l+2}}{\bar{\sigma}_l} \geq 0$$

$\rightarrow$ not possible (see arXiv).
Arbitrary GMMs: Consider 2-component GMM

\[ m(x) = \frac{1}{2} p(x; -\frac{1}{2}, 10^{-5}) + \frac{1}{2} p(x; \frac{1}{2}, 10^{-5}) \]

\[ H(MC) = -9.400517405407735 \]

1. MEUB: 0. 9999999999958284
2. MEUB: 0. 7257913528258293
3. MEUB: 0. 5863457882025702
4. MEUB: 0. 4983017544470345
5. MEUB: 0. 43651349327316713
6. MEUB: 0. 390267211711506
7. MEUB: 0. 3541034307385086
8. MEUB: 0. 32490700997403515
9. MEUB: 0. 3007543998901125
10. MEUB: 0. 2803860698295638
11. MEUB: 0. 2629389102447494
12. MEUB: 0. 24779955106708096
13. MEUB: 0. 23451890956649502
14. MEUB: 0. 2275989562550735
15. MEUB: 0. 21226407836562905
16. MEUB: 0. 2028296978359989
17. MEUB: 0. 19429672922288133
18. MEUB: 0. 18653647716356042
19. MEUB: 0. 17944416377804479
20. MEUB: 0. 1729335449648154
21. MEUB: 0. 16693293142890442
22. MEUB: 0. 16138220185001972
23. MEUB: 0. 1562305292037145
24. MEUB: 0. 15143462788690765
25. MEUB: 0. 14695738668300817
26. MEUB: 0. 14276679134420478
27. MEUB: 0. 13883506718452443
28. MEUB: 0. 13513799065560295
29. MEUB: 0. 13165433203558718
30. MEUB: 0. 128365400080724268
31. MEUB: 0. 12525467216646413
Contributions and conclusion

▶ Introduced the class of *Absolute Monomial Exponential Families* (AMEFs) with closed-form log-normalizer,

▶ Reported closed-form formulæ for the differential entropy of AMEFs,

▶ Calculated the exact *non-centered absolute geometric moments* for a Gaussian Mixture Model (GMMs),

▶ Apply MaxEnt Upper Bounds induced by AMEFs to GMMs: All upper bounds are potentially useful for non-centered GMMs (But for zero centered-GMMs, only the first two bounds are enough.)

▶ Recommend $\min(U_1, U_2)$ in applications! (not only $U_2$)

▶ Reproducible research with code
  https://www.lix.polytechnique.fr/~nielsen/MEUB/
L.D. Brown.

*Fundamentals of Statistical Exponential Families: With Applications in Statistical Decision Theory.*

Thomas M Cover and Joy A Thomas.

*Elements of information theory.*

Aapo Hyvarinen, Juha Karhunen, and Erkki Oja.

*Independent component analysis.*

Edwin T Jaynes.

*Information theory and statistical mechanics.*

Edwin T Jaynes.

*Information theory and statistical mechanics II.*

Joseph V Michalowicz, Jonathan M Nichols, and Frank Bucholtz.

Calculation of differential entropy for a mixed Gaussian distribution.


*Handbook of Differential Entropy.*

Ali Mohammad-Djafari.

A Matlab program to calculate the maximum entropy distributions.
Frank Nielsen and Richard Nock.
Entropies and cross-entropies of exponential families.

Sumio Watanabe, Keisuke Yamazaki, and Miki Aoyagi.
Kullback information of normal mixture is not an analytic function.
Differential entropy of a location-scale family

Density of a location-scale distribution: \( p(x; \mu, \sigma) = \frac{1}{\sigma} p_0\left(\frac{x-\mu}{\sigma}\right) \)
\( \mu \in \mathbb{R} \): location parameter and \( \sigma > 0 \): dispersion parameter.

Change of variable \( y = \frac{x-\mu}{\sigma} \) (with \( dy = \frac{dy}{\sigma} \)) in the integral to get:

\[
H(X) &= \int_{x=-\infty}^{+\infty} -\frac{1}{\sigma} p_0\left(\frac{x-\mu}{\sigma}\right) \left( \log \frac{1}{\sigma} p_0\left(\frac{x-\mu}{\sigma}\right) \right) \, dx, \\
&= \int_{y=-\infty}^{+\infty} -p_0(y) \left( \log p_0(y) - \log \sigma \right), \\
&= H(X_0) + \log \sigma.
\]

\( \rightarrow \) always independent of the location parameter \( \mu \)
Non-central even geometric moments of a normal distribution

| Even $l$ | $A_l = E[|X|^l] = E[X^l] = \sum_{i=0}^{\lfloor l/2 \rfloor} \binom{l}{2i}(2i - 1)!! \mu^{l-2i}\sigma^{2i}$ |
|----------|--------------------------------------------------------------------------------|
| 2        | $\mu^2 + \sigma^2$                                                               |
| 4        | $\mu^4 + 6\mu^2\sigma^2 + 3\sigma^4$                                             |
| 6        | $\mu^6 + 15\mu^4\sigma^2 + 45\mu^2\sigma^4 + 15\sigma^6$                          |
| 8        | $\mu^8 + 28\mu^6\sigma^2 + 210\mu^4\sigma^4 + 420\mu^2\sigma^6 + 105\sigma^8$ |
| 10       | $\mu^{10} + 45\mu^8\sigma^2 + 630\mu^6\sigma^4 + 3150\mu^4\sigma^6 + 4725\mu^2\sigma^8 + 945\sigma^{10}$ |
Non-central odd geometric moments of a normal distribution

\[ A_l = E[|X|] = C_l(\mu, \sigma)\sqrt{\frac{2}{\pi}} \exp\left(-\frac{\mu^2}{2\sigma^2}\right) + D_l(\mu, \sigma)\text{erf}\left(\frac{\mu}{\sqrt{2}\sigma}\right) \]

<table>
<thead>
<tr>
<th>Odd \ l</th>
<th>[ A_l = \frac{\sigma}{\sqrt{\frac{2}{\pi}}} \exp\left(-\frac{\mu^2}{2\sigma^2}\right) + \mu \text{erf}\left(\frac{\mu}{\sqrt{2}\sigma}\right) ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[ (2\sigma^3 + \mu^2\sigma)\sqrt{\frac{2}{\pi}} \exp\left(-\frac{\mu^2}{2\sigma^2}\right) + (\mu^3 + 3\mu^2\sigma^2)\text{erf}\left(\frac{\mu}{\sqrt{2}\sigma}\right) ]</td>
</tr>
<tr>
<td>3</td>
<td>[ (8\sigma^5 + 9\mu^2\sigma^3 + \mu^4\sigma)\sqrt{\frac{2}{\pi}} \exp\left(-\frac{\mu^2}{2\sigma^2}\right) + (\mu^5 + 10\mu^3\sigma^2 + 15\mu^4\sigma^4)\text{erf}\left(\frac{\mu}{\sqrt{2}\sigma}\right) ]</td>
</tr>
<tr>
<td>5</td>
<td>[ (48\sigma^7 + 87\mu^2\sigma^5 + 20\mu^4\sigma^3 + \mu^6\sigma)\sqrt{\frac{2}{\pi}} \exp\left(-\frac{\mu^2}{2\sigma^2}\right) + (\mu^7 + 21\mu^5\sigma^2 + 105\mu^3\sigma^4 + 105\mu^5\sigma^6)\text{erf}\left(\frac{\mu}{\sqrt{2}\sigma}\right) ]</td>
</tr>
<tr>
<td>7</td>
<td>[ (384\sigma^9 + 975\mu^2\sigma^7 + 345\mu^4\sigma^5 + 35\mu^6\sigma^3 + \mu^8\sigma)\sqrt{\frac{2}{\pi}} \exp\left(-\frac{\mu^2}{2\sigma^2}\right) + (\mu^9 + 36\mu^7\sigma^2 + 378\mu^5\sigma^4 + 1260\mu^3\sigma^6 + 945\mu^8\sigma^8)\text{erf}\left(\frac{\mu}{\sqrt{2}\sigma}\right) ]</td>
</tr>
</tbody>
</table>
assume (theta<0);
F(theta) := log(integrate(exp(theta*abs(x)^5),x,-inf,inf));
integrate(exp(theta*abs(x)^5-F(theta)),x,-inf,inf);
/* Binomial expansion */
binomialExpansion(i, p, q) := if i = 1 then p+q
else expand((p+q)*binomialExpansion(i-1, p, q));

/* The standard distribution (here, normal) */
p0(y) := exp(-y^2/2)/sqrt(2*pi);

/* Even moment */
absEvenMoment(mu, sigma, l) :=
ratexpand(ratsimp(integrate(factor(expand(binomialExpansion(l, mu, y*sigma)))*p0(y), y, -inf, inf)));

/* Odd moment */
absOddMoment(mu, sigma, l) :=
ratexpand(ratsimp(integrate(factor(expand(binomialExpansion(l, mu, y*sigma)))*p0(y), y, -mu/sigma, inf)
-integrate(factor(expand(binomialExpansion(l, mu, y*sigma)))*p0(y), y, -inf, -mu/sigma)));

/* General: Maxima does not give a closed-form formula because of the absolute value */
absMoment(mu, sigma, l) :=
ratexpand(ratsimp(integrate(abs(factor(expand(binomialExpansion(l, mu, y*sigma))))*p0(y), y, -inf, inf)));

assume(sigma>0);
assume(mu>0); /* maxima needs to branch condition */
absEvenMoment(mu, sigma, 8);
absOddMoment(mu, sigma, 7);
absMoment \((\mu, \sigma, l) := \) 

ratexpand \( \left( \text{ratsimp} \left( \int_{-\infty}^{\infty} \text{factor} \left( \text{expand} \left( \text{binomialExpansion} \left( l, \mu, \sigma \right) \right) \right) \left| p_0 \left( y \right) \, dy \right) \right) \) \)

\( \sigma > 0 \)

\( \mu > 0 \)

\( \frac{105}{\sqrt{\pi}} \sigma^6 + \frac{420}{\sqrt{\pi}} \mu^2 \sigma^6 + \frac{210}{\sqrt{\pi}} \mu^4 \sigma^4 + \frac{28}{\sqrt{\pi}} \mu^6 \sigma^2 + \frac{\mu^8}{\sqrt{\pi}} \)

\( \frac{32^{3/2} \sigma^7 \text{erf} \left( \frac{\mu}{\sqrt{2} \sigma} \right) \sigma^4}{\sqrt{\pi}} + \frac{87 \sqrt{2} \mu^2 \sigma^5 \text{erf} \left( \frac{\mu}{\sqrt{2} \sigma} \right) \sigma^2}{\sqrt{\pi}} + \frac{52^{5/2} \mu^4 \sigma^3 \text{erf} \left( \frac{\mu}{\sqrt{2} \sigma} \right) \sigma^2}{\sqrt{\pi}} + \frac{\sqrt{2} \mu^6 \sigma^6 \text{erf} \left( \frac{\mu}{\sqrt{2} \sigma} \right) \sigma^2}{\sqrt{\pi}} + \frac{105 \mu^8 \text{erf} \left( \frac{\mu}{\sqrt{2} \sigma} \right) \sigma^6}{\sqrt{\pi}} \)

\( + \frac{105}{\sqrt{\pi}} \mu^3 \text{erf} \left( \frac{\mu}{\sqrt{2} \sigma} \right) \sigma^4 + \frac{21}{\sqrt{\pi}} \mu^5 \text{erf} \left( \frac{\mu}{\sqrt{2} \sigma} \right) \sigma^2 + \frac{\sqrt{\pi} \mu^7 \text{erf} \left( \frac{\mu}{\sqrt{2} \sigma} \right)}{\sqrt{\pi}} \)